Investigating the potential for disease spread, prevention, and control in the Ontario equine population

by

Kelsey Leigh Spence

A Thesis
presented to
The University of Guelph

In partial fulfilment of requirements
for the degree of
Doctor of Philosophy
in
Population Medicine

Guelph, Ontario, Canada

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ABSTRACT

INVESTIGATING THE POTENTIAL FOR DISEASE SPREAD, PREVENTION, AND CONTROL IN THE ONTARIO EQUINE POPULATION

Kelsey Leigh Spence
University of Guelph, 2017

Advisors:
Dr. Amy Greer
Dr. Terri O’Sullivan

This thesis aims to investigate the potential for disease spread in the Ontario equine population, and to describe the implications for disease prevention and control. A series of research projects were undertaken to address existing knowledge gaps surrounding the Ontario equine population, including descriptions of horse characteristics, the nature and extent of horse movements, and the expected efficacy of common biosecurity practices. Questionnaires were used to describe horse characteristics (including age, vaccinations, and travel patterns), and facility characteristics (including number of boarded horses and their sport/competition disciplines). Network analysis was used to synthesize questionnaire responses to describe the connectivity between horses and horse facilities. Agent-based models were used to explore potential disease spread within the network of horse contacts, and to investigate the impact of biosecurity and infection control measures (i.e., vaccination, reduced horse-to-horse contact, and quarantine). There are several important findings from this thesis. First, descriptive analyses suggested that horse owners are currently vaccinating their horse(s) and reducing opportunities for direct and indirect horse contact. In particular, owners with horses that participated in competitive disciplines reported higher levels of vaccine coverage for various equine pathogens, compared to owners with horses that participated in either leisure or racing activities. Second, agent-based models demonstrated the importance of using multiple biosecurity and infection control measures in combination. The
most effective strategies to minimize the extent of a simulated outbreak were those that combined disease prevention (e.g., increased vaccine coverage) with disease control (e.g., quarantine upon returning home from a competition). Third, participants reported travelling frequently with their horse(s) to attend various competitions, training clinics, and leisure activities. The description of horse movement patterns provides valuable data that can contribute to future research exploring the characteristics of highly connected horses and facilities. The combined approach of questionnaires, network analysis, and simulation models has provided insight into the Ontario equine population, which can better inform the use of effective disease prevention and control strategies. This thesis represents a fundamental contribution to the ongoing discussion within the Ontario equine industry regarding the refinement of existing disease prevention and control strategies.
ACKNOWLEDGEMENTS

First and foremost, I would like to thank the members of my advisory committee, Drs. Amy Greer, Terri O’Sullivan, and Zvonimir Poljak. I am grateful for your support, guidance, encouragement, and dedication to my academic and personal growth. To my co-advisors, Amy and Terri, thank you for believing in me and providing me with every opportunity possible. It has truly been a pleasure working as a team and I look forward to future collaborations.

I am especially grateful to the horse owners who volunteered their time to participate in this research, and to the organizations that assisted in participant recruitment. Thank you to Beverly Goh and Cyndi Boughen for assistance during data collection, and Wayne Johnston and Karen Richardson for assistance during data entry.

I have been surrounded by great staff, colleagues, and friends in the Department of Population Medicine. Thank you to Dr. Andria Jones-Bitton for the opportunity to serve as a GTA for three semesters; I am grateful for everything I have learned, from how to teach an epidemiology class, to how to increase my FitBit steps. Thank you to my lab-mates for making this journey more enjoyable (and for attending every meeting of the Disease Modeling Club).

I would like to gratefully acknowledge the funding partners for this project: Equine Guelph, the Ontario Ministry of Food, Agriculture, and Rural Affairs (OMAFRA), and the Canada Research Chairs program, as well my graduate funding through the Ontario Veterinary College Scholarship and the Ontario Graduate Scholarship.

Lastly, thank you to my incredible family and friends for your patience, love, and support. To Anthony (and Jackson), words cannot express my gratitude for always being a source of inspiration and encouragement. I look forward to our next adventure together.
STATEMENT OF WORK

**Chapter 2:** Kelsey Spence conducted a search of the peer-reviewed literature for model input parameters. The agent-based simulation model was designed and created by Kelsey Spence with assistance from Dr. Amy Greer. All descriptive and mathematical analyses were conducted by Kelsey Spence, with input from Drs. Amy Greer, Terri O’Sullivan, and Zvonimir Poljak. The manuscript was written by Kelsey Spence, and reviewed and edited by Drs. Amy Greer, Terri O’Sullivan, and Zvonimir Poljak.

**Chapter 3:** The initial research proposal and questionnaire were prepared by Drs. Amy Greer and Terri O’Sullivan. Data were collected by Dr. Amy Greer, Dr. Terri O’Sullivan, Beverly Goh, and Kelsey Spence. Data were entered, cleaned, and analyzed by Kelsey Spence, with input from Drs. Amy Greer, Terri O’Sullivan, and Zvonimir Poljak. The manuscript was written by Kelsey Spence, and reviewed and edited by Drs. Amy Greer, Terri O’Sullivan, and Zvonimir Poljak.

**Chapter 4:** Using data collected from Chapter 3, Kelsey Spence built the agent-based simulation model with assistance from Dr. Amy Greer. The interventions tested in the model were chosen in collaboration with Drs. Amy Greer, Terri O’Sullivan, and Zvonimir Poljak. All descriptive and mathematical analyses were conducted by Kelsey Spence, with input from Drs. Amy Greer, Terri O’Sullivan, and Zvonimir Poljak. The manuscript was written by Kelsey Spence, and reviewed and edited by Drs. Amy Greer, Terri O’Sullivan, and Zvonimir Poljak.

**Chapter 5:** The questionnaire was designed by Kelsey Spence, with input from Drs. Amy Greer, Terri O’Sullivan, and Zvonimir Poljak. Participants were recruited with assistance from various
organizations within the equine industry, including Equine Guelph, the Ontario Equestrian Federation, the Ontario Association of Equine Practitioners, the Ontario Animal Health Network, Equestrian Canada, and the Ontario Veterinary College. In-person participant recruitment was completed by Kelsey Spence and Cyndi Boughen. The participant panel and their questionnaire responses were maintained by Kelsey Spence throughout the longitudinal study. Wayne Johnston assisted with the creation of the database for data entry. Kelsey Spence cleaned the data, and it was entered into the database by Karen Richardson. Data entry was validated by Kelsey Spence. All descriptive and statistical analyses were conducted by Kelsey Spence, with input from Drs. Amy Greer, Terri O’Sullivan, and Zvonimir Poljak. The manuscript was written by Kelsey Spence, and reviewed and edited by Drs. Amy Greer, Terri O’Sullivan, and Zvonimir Poljak.
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<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>AUD</td>
<td>Australian dollar</td>
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<tr>
<td>CAD</td>
<td>Canadian dollar</td>
</tr>
<tr>
<td>EEE/WEE</td>
<td>Eastern/Western equine encephalitis</td>
</tr>
<tr>
<td>EHV</td>
<td>Equine herpesvirus</td>
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<tr>
<td>EI</td>
<td>Equine influenza</td>
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<tr>
<td>ELISA</td>
<td>Enzyme-linked immunosorbent assay</td>
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<tr>
<td>KM</td>
<td>Kilometre</td>
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<tr>
<td>KTT</td>
<td>Knowledge translation and transfer</td>
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<tr>
<td>MLV</td>
<td>Modified live virus</td>
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<tr>
<td>qRT-PCR</td>
<td>Quantitative reverse transcription polymerase chain reaction</td>
</tr>
<tr>
<td>$R_0$</td>
<td>Basic reproductive number</td>
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<tr>
<td>Re</td>
<td>Effective reproductive number</td>
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<tr>
<td>RT-PCR</td>
<td>Reverse transcription polymerase chain reaction</td>
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<tr>
<td>SB1</td>
<td>Stabling barn #1</td>
</tr>
<tr>
<td>SB2</td>
<td>Stabling barn #2</td>
</tr>
<tr>
<td>SD</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>SEIR</td>
<td>Susceptible-exposed-infectious-recovered</td>
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<tr>
<td>SEIRV</td>
<td>Susceptible-exposed-infectious-recovered-vaccinated</td>
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<tr>
<td>SI</td>
<td>Ship-ins</td>
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<tr>
<td>UK</td>
<td>United Kingdom</td>
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<tr>
<td>USA</td>
<td>United States of America</td>
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<td>WNV</td>
<td>West Nile virus</td>
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CHAPTER ONE

Introduction, literature review, and thesis objectives

1.1 Introduction

The structure of the international agricultural industry poses challenges for the prevention and control of infectious diseases. Risk factors for disease introduction and spread can differ between livestock facilities, and the connections facilitated by animal movements can add additional challenges for describing the associated risks (Fèvre et al., 2006). Past explorations of livestock movements were prompted by major disease incursions, such as the 2001 UK foot-and-mouth disease epidemic (Ortiz-Pelaez et al., 2006; Webb, 2006; Dubé et al., 2009). The potential for similar outbreaks has caused some countries to implement national requirements for the traceability of livestock movements (Volkova et al., 2010; Büttner et al., 2013; Porphyre et al., 2016). Research surrounding the potential for disease spread in livestock populations has emphasized the potential welfare, political, and economic consequences of disease within the livestock industry (Fèvre et al., 2006).

The involvement of cattle, pigs, and sheep in various food and agricultural industries has elicited an abundance of research on these populations (Kao et al., 2006; Dubé et al., 2009). In contrast, similar research to describe populations of horses is associated with a variety of challenges. In Ontario, Canada, horses are defined as livestock (Livestock Identification Act, 1990), but are often regarded as companion animals by their owners and society. The variability of an owner’s use of their horse and the frequency of their movements contributes to the differences in the associated risks of disease introduction and spread in the population (Sánchez-Matamoros et al., 2013). In some countries, horses are included in national traceability
requirements, and therefore their characteristics, movements, and time-varying spatial locations can be described (Bell and Drury-Klein, 2011; Firestone et al., 2012b; Sánchez-Matamoros et al., 2013). In countries without these requirements, descriptions of horse populations have been gathered through interview and questionnaire-based methods (Hayama et al., 2010; Boden et al., 2013; Rosanowski et al., 2013; Liebenberg et al., 2016). Horses are not included in traceability requirements in Canada, and therefore descriptions of horse populations have been limited to the Canadian Equine Industry Study (conducted in 2010), and the Canadian Census of Agriculture (conducted every five years) (Statistics Canada, 2016).

Despite the limited descriptive data published on the Canadian equine industry, it represents a valuable component of the Canadian economy, contributing over $19 billion CAD in 2010 (Equine Canada, 2010). Horses within the industry are highly mobile, travelling locally, nationally, and internationally to participate in shows and sporting events. The results of the 2016 Census of Agriculture estimated that there were 64,536 horses and ponies residing on 9,294 farms in Ontario (Statistics Canada, 2016). However, individual horse characteristics, such as vaccination status, the frequency of horse movements, and their owners’ use of biosecurity and infection control measures, are not reported. Improved, up-to-date descriptive information is an essential requirement for using evidence-based decision-making to help improve the prevention and control of diseases in the Ontario equine population.

1.2 Outbreaks of infectious disease in horses

1.2.1 Historical significance

In September 1872, an influenza-like illness was reported on a horse farm north of Toronto, Ontario (Judson, 1873). From Toronto, the disease was reported to “extend in every
direction” into the United States and Central America (Judson, 1873; Morens and Taubenberger, 2010). Correspondence from individuals who experienced the outbreak described the disease affecting nearly all horses, leading to deserted city streets, a transportation standstill, and market closures (Judson, 1873). In the United States, the disease was described as causing a “shutdown” of the country, preventing transportation of physicians, firefighters, and other goods and services (Morens and Taubenberger, 2010).

During the equine influenza outbreak of 1872, humans were almost entirely dependent on horses for a variety of purposes, ranging from transportation to a source of income. While the use of horses today has shifted to mostly recreational, companion, or competition purposes, horses remain significant to the human population. Estimates from the 2007 Australian equine influenza outbreak reported $380 million AUD in financial losses to horse owners, horse associations, and businesses (Smyth et al., 2011). Furthermore, the prevalence of “very high psychological distress” in horse owners and industry members during and after the outbreak was five times the level of distress reported in the general population (Taylor et al., 2008). The closely intertwined relationship between humans and horses highlights the historical, economic, and emotional significance of equine disease events.

1.2.2 Identifying the risk of disease introduction and spread

Baseline risk of disease

Estimates of the prevalence or incidence of disease in a population can inform the baseline risk of disease introduction and spread. In Canada, equine diseases which require reporting differ at the provincial and national level, and the timeliness of reporting varies from immediately notifiable to annually notifiable (Ontario Ministry of Agriculture Food and Rural
Affairs, 2010). Furthermore, most published estimates of the prevalence/incidence of disease are from specific outbreak investigations due to the absence of a surveillance system (Weese, 2014). To increase awareness of the incidence of equine disease in the United States, the Equine Disease Communication Center was created to act as a communication mechanism for horse owners and veterinary professionals (White and Traub-Dargatz, 2012). The absence of a comparable system in Canada makes it challenging to identify the prevalence and incidence of various equine diseases, especially for those that are non-reportable.

**Identification and location of horses**

Demographic information, such as the number and distribution of horses in a population, can better inform the development of disease management protocols. Population demographics can identify subgroups at higher risk for exposure to disease, including younger/older horses, unvaccinated horses, and those that travel frequently (Wright and Kenney, 2004). In Denmark, a survey of stakeholders (including veterinarians, researchers, and horse industry members) demonstrated that 86% of respondents would be willing to provide horse demographic data to a central database (Hartig et al., 2013). The authors note that the most common motivator for stakeholder contribution to a central database was the belief that it would be beneficial to horse health and welfare (Hartig et al., 2013). A similar approach for data collection for Ontario horses would provide the equine industry with up-to-date information on demographic characteristics of horses within the province; however, it is not currently under consideration.
Horse movements

Horse movements provide opportunities for disease introduction and spread because of the potential for contact between horses at their destination. The mixing of horses at these locations can pose a risk for disease spread due to the unknown health status of any additional horses, and uncertainty regarding the biosecurity practices that may be undertaken by other horse owners (Canadian Food Inspection Agency, 2016). The introduction and spread of equine disease due to international movements is of particular importance due to potential introductions of exotic diseases into the destination country (Dominguez et al., 2015). In a systematic review of equine disease events following international movements, 87% of events were not contained by post-arrival quarantine procedures and resulted in the introduction of the disease into the destination country (Dominguez et al., 2015). The authors’ conclusions supported the importance of collecting equine movement patterns to quantify the risk of equine disease events occurring following international movements (Dominguez et al., 2015).

There have been notable instances of disease outbreaks associated with local horse movements as horses attend competitions, events, training, or races. During the 2007 Australian equine influenza outbreak, horse movements were described extensively to determine their impact on the spread of the disease to over 10,000 premises (Bell and Drury-Klein, 2011; Firestone et al., 2011; Moloney, 2011; Sergeant et al., 2011). In 2011, an outbreak of equine herpesvirus occurred after horses attended a national event in Ogden, Utah, which resulted in 242 exposed horse premises in 19 states and 3 Canadian provinces (Traub-Dargatz et al., 2004). While these examples highlight the potential risk of disease spread following horse movements, further information, including the frequency of movements and the level of mixing occurring at the destinations, is required to quantify the probability of an outbreak (Wood et al., 2003).
1.2.3 Disease prevention and control

The prevention and control of equine disease relies on the sustained use of biosecurity and infection control measures. Biosecurity measures are defined as strategies used to prevent the introduction of a pathogen into a population, and infection control measures are defined as strategies used to limit the impact of a pathogen after its introduction (Weese, 2014). The general principles of biosecurity and infection control measures involve: 1) decreasing exposure to pathogens, generally by reducing direct contact between horses and/or indirect contact with contaminated items; 2) cleaning and disinfection to reduce the amount of a pathogen present in the environment; and 3) decreasing the susceptibility of horses to a given pathogen (e.g., using vaccination) (Canadian Food Inspection Agency, 2016). Most equine infection control recommendations are based on these principles; however, there are many important questions surrounding the efficacy of these programs. For instance, further research is required to inform the use of effective prevention measures, such as optimal quarantine periods and strategies for the cleaning and disinfection of equine facilities (Weese, 2014).

Outbreak response and emergency management protocols are often established after experiencing an equine disease event (Perkins et al., 2011; Scott-Orr, 2011). During the 2007 Australian equine influenza outbreak, infection control measures, such as disinfection of clothes, equipment, and vehicles, were implemented following a public awareness program to encourage disease reporting (Scott-Orr, 2011). Vaccination during the outbreak response included ring vaccination surrounding areas with known cases of disease, predictive vaccination of horses identified as potential contributors to disease spread (e.g., racehorses and international competitors), and blanket vaccination of all individuals in an area (Perkins et al., 2011). During the 2007 equine influenza outbreak in Japan, infection control interventions, including
movement restrictions, isolation, and quarantine, reduced the number of secondary transmissions by up to 99.5% (Nishiura and Satou, 2010). In situations where the best outbreak response program is unknown, alternate methods, such as network analysis and mathematical modeling, have been used to test potential strategies to inform outbreak preparedness (Park et al., 2003; Ward et al., 2009; Firestone et al., 2011, 2012a; Rosanowski et al., 2016).

In 2016, the Canadian Food Inspection Agency, in collaboration with the equine industry, outlined biosecurity standards for horses and horse facilities in Canada (Canadian Food Inspection Agency, 2016). The successful implementation of recommended biosecurity and infection control measures relies on compliance from horse owners and facility managers. Weese (2014) reported that Ontario horse owners demonstrated a high “accepted nature” of disease, as 80 to 100% of horse owners expected that their newly purchased yearling would develop a disease. This “accepted nature” of disease poses significant risks if individuals are unwilling to change their behaviour regarding compliance with biosecurity and infection control practices (Weese, 2014). In the United States, a survey of horse owners revealed that 80% of respondents either did not have or were unfamiliar with the biosecurity measures used at their horse’s facility (Vanderman et al., 2009). Similarly, a survey of horse facilities in New Zealand demonstrated that the general, day-to-day usage of biosecurity measures at the facilities would be insufficient to prevent disease introduction (Rosanowski et al., 2012). The lack of awareness regarding the benefits of biosecurity and infection control measures suggests that alternate communication strategies are required to demonstrate their importance.
1.3 Network analysis

While network analysis has been applied to a variety of topics since the 1730s, it became popularized in the 1920s with the concept of “Six Degrees of Separation”, the idea that everyone in the world could be connected through links of six or fewer people (Borgatti et al., 2013). Network analysis is a branch of graph theory, which is the description and analysis of the properties of a graph (Wasserman and Faust, 1994). The application of graph theory aims to explore how and why the components within a graph are connected (Martínez-López et al., 2009). Disciplines that apply graph theory, including sociology, geography, and epidemiology, work under the general hypothesis that the relationship of a group of individuals depends on the structure of the connections between them (Borgatti et al., 2013).

Networks describe individual entities, including people, animals, or locations, using nodes (also called vertices or actors), and the connections between these individuals are described by edges (also called lines or arcs) (Wasserman and Faust, 1994). The connections within a network can be undirected to represent reciprocal relationships (e.g., friendships), or directed to represent relationships that are unidirectional in nature (e.g., movements) (Borgatti et al., 2013). Furthermore, the connections described within a network can include relational states, which are continuously persistent connections between nodes (e.g., “boards/stables horses with”), or relational events, which represent discrete events (e.g., a movement of an animal between two locations) (Borgatti et al., 2013). Connections can be analyzed at the different levels: 1) the node, to describe its individual connections; 2) the dyad (i.e., pair of nodes), to describe the likelihood of that particular connection existing; or 3) the network, to define any broader patterns or characteristics of the connections (Borgatti et al., 2013).
1.3.1 Usage in veterinary research

The use of network analysis in human epidemiological research is well established, and it has been most notably used to analyze networks of the transmission of human immunodeficiency virus (Auerbach et al., 1984; Klovdahl et al., 1994) and tuberculosis (Klovdahl et al., 2001; Andre et al., 2007). In contrast, the use of network analysis in veterinary research has only arisen within the past 15 years. Christley and French (2003) used network analysis to describe the contact structure of horses attending races in the UK over a one-week period. This undirected network consisted of horse trainers (nodes), and connections between trainers occurred when two trainers raced together (edges) (Christley and French, 2003). Following the work of Christley and French (2003), network analysis has been used to characterize the movements of cattle, pigs, sheep, and other livestock animals. The recognized importance of large disease outbreaks, such as the 2001 foot-and-mouth disease outbreak in the UK, prompted descriptions of various movement networks, with examples including movements of sheep attending agricultural shows in Great Britain (Webb, 2005, 2006), movements of sheep and cattle in New Zealand (Sanson, 2005), and livestock movements prior to the 2001 foot-and-mouth disease outbreak (Ortiz-Pelaez et al., 2006). The conclusions drawn from these studies highlight the heterogeneity among contacts in various agricultural sectors, and the potential impact of these connections on disease spread (Dubé et al., 2009).

In comparison to other livestock populations, the use of network analysis in horse populations has experienced some challenges. The unique structure of a horse population depends on the variety of uses for the horses, the types of facilities in which they live, and the network formed by their movements (Martínez-López et al., 2009). Horses are often considered pets or companion animals, and as such, they tend to be excluded from livestock traceability
programs (Sanchez-Matamoros et al. 2013). In some instances, horse movement patterns have been characterized using data collected from existing databases, such as in Australia (Bell and Drury-Klein, 2011) and Spain (Sánchez-Matamoros et al., 2013). Alternate methods, including contact tracing (Firestone et al., 2011) and interview/questionnaire-based methods (Hayama et al., 2010; Boden et al., 2013; Rosanowski et al., 2013; Liebenberg et al., 2016), have also been used to describe horse movements.

1.3.2 Types of networks

Contact networks and movement networks

A contact network describes the potential for contact between individuals. Examples of contact networks include a network of sheep in Great Britain (Webb, 2005) and a network of horses with shared race trainers in the UK (Christley and French, 2003). A contact network is often undirected to represent a potential reciprocal relationship between two individuals (Keeling and Eames, 2005; Firestone et al., 2011). In contrast, movement networks infer the potential for contact between individuals based on shared movements between locations. Movement networks are often represented as directed networks, where the nodes represent locations, and the edges represent directed movements of animals between two locations (Dubé et al., 2009).

Static and dynamic networks

Static and dynamic networks are distinguished based on how the connections are represented and visualized. Static networks represent a group of nodes and edges that do not change over time (Borgatti et al., 2013). In dynamic networks, the nodes and/or the edges within the network can change over time (Kolaczyk and Csardi, 2014). In general, static networks are
best used when the connections are stable (i.e., relational states) (Bansal et al., 2010; Borgatti et al., 2013), and dynamic networks are best used when the connections are changing (i.e., relational events) (Borgatti et al., 2013).

The choice of a static or dynamic network depends on the particular use of the network and the disease of interest. Dubé et al. (2009) suggested that static representations of a dynamic network are acceptable if the changes among the connections in the network are slow relative to the transmission of the pathogen of interest. In contrast, Vernon and Keeling (2009) demonstrated that any static representation of cattle movements in the UK did not accurately represent the potential transmission dynamics in comparison to the dynamic network. The authors suggest that both network representation and disease dynamics are key drivers in the description of potential disease spread (Vernon and Keeling, 2009). Characteristics that could be misrepresented by the use of static networks instead of dynamic networks include demographic changes (e.g., births and deaths), changes in social relationships (i.e., removing edges), movement and travel patterns, and seasonality (Bansal et al., 2010).

There are a variety of methods that can be used to analyze and visualize dynamic networks. In some instances, the real-time structure of the network can be replicated so that the nodes/edges disappear or appear over time (Kolaczyk and Csardi, 2014). More commonly, dynamic networks are divided into “snapshots” and analyzed/visualized within smaller time periods (Kolaczyk and Csardi, 2014). One disadvantage of dividing dynamic networks into snapshots is that the temporal aspect of the network is lost, as all edges that connect nodes in a particular time period are maintained as static (Kolaczyk and Csardi, 2014). The resolution at which snapshots of a dynamic network are analyzed can have implications for the definition of a contact, and therefore the structure of the observed network. At a high resolution, Chen et al.
Dutta et al. (2014) investigated on-farm real-time contact networks of cattle. While informative, network data at this level of detail are often challenging to obtain. Dutta et al. (2014) characterized a network of cattle movements in France over different time periods to determine if aggregated snapshots could represent the true structure of the network. The authors concluded that while a dynamic network should be used where possible, the distribution of network characteristics remained relatively constant within an 8-16 week period (Dutta et al., 2014). Furthermore, Büttner et al. (2013) investigated the changes of the network structure of swine movements at different time scales, and determined that while yearly networks inaccurately represent the risk of disease spread due to aggregation, characterization of time periods during which movements would likely be different (e.g., seasonal time periods) would be a reasonable alternative to detailed dynamic networks.

One- and two-mode networks

A one-mode network consists of connections between a single entity (e.g., horses) (Borgatti et al., 2013). In contrast, a two-mode network consists of connections between two types of entities, for example, horses and locations (Borgatti et al., 2013). Two-mode data can be further distinguished as bipartite if the two entities do not connect within their own class (e.g., horses can only be connected to locations, and vice versa) (Borgatti et al., 2013). Two-mode data have several purposes in network analysis. In some instances, two-mode data are collected to describe the relationships among the two entities, such as describing common agricultural events that sheep have attended (Webb, 2006). Otherwise, two-mode data are often collected as a first step in the construction of a one-mode network. This allows connections between entities to be inferred based on their common connections; for example, connections between horses attending
equestrian shows can be inferred based on co-attendance at the same show (Borgatti and Everett, 1997). The construction of a one-mode network from a two-mode network must be interpreted with caution, as it provides only an indication of the potential for contact due to a common connection (Borgatti and Everett, 1997).

1.3.3 Collecting social network data

Database approaches

Databases of livestock movements can provide detailed information to inform network analysis. For example, Bigras-Poulin et al. (2006) analyzed the network of the Danish cattle industry using a database containing detailed descriptions of cattle premises within the country. Büttner et al. (2013) used a database of swine movements registered in northern Germany to evaluate changes in the movement network over time and to determine how these changes could impact potential disease spread. Sánchez-Matamoros et al. (2013) used a database of horse movements in regions of Spain to describe the connectivity of the horse population. Information available in this database included the date(s) of movements, the number of animals moved, and the geographical location of the departure/destination location (Sánchez-Matamoros et al., 2013). By characterizing equine movements during a time without an ongoing outbreak, the authors described the natural travel patterns uninfluenced by any disease control measures (Sánchez-Matamoros et al., 2013).

Questionnaire-based approaches

In countries where movement databases are unavailable, alternate methods must be used to describe the underlying network structure of the population. Hayama et al. (2010) used a
questionnaire to collect information on the movement patterns of non-racehorses in Japan to determine their effect on potential disease spread. The authors used the questionnaire results to stratify the horse population into different sectors based on the use of the horse to better characterize mixing between the sectors (Hayama et al., 2010). Interview and questionnaire-based methods have also been successful at describing movement patterns in Great Britain (Boden et al., 2013), New Zealand (Rosanowski et al., 2013), and South Africa (Liebenberg et al., 2016).

A common method used to collect movement data are diary-based questionnaires. Diary-based questionnaires require the individual to record all movements over a defined period of time (Mossong et al., 2008). For example, Sanson (2005) used diary-based questionnaires to describe movements of people, animals, vehicles, and equipment during two 3-week periods (a self-defined “busy” period and a “quiet” period). One limitation of questionnaire-based approaches is that data collection relies heavily on the efforts of the participant (Borgatti et al., 2013). This, in part, contributes to the potential for a low response rate (e.g., Sanson (2005) had a response rate of 43%). Lastly, because the data are collected at the individual-level, the creation of a comprehensive network from the individual reports may not be possible, for example, if individuals name different locations in a movement network (Keeling and Eames, 2005). The lack of a comprehensive network will result in a disconnected network, which may or may not be representative of the true connections within the population.

1.3.4 Generalizability

The network of an entire population can rarely be characterized due to the inability to sample the entire population, and/or the inability of individuals to accurately recall their
connections over a defined time frame (Keeling and Eames, 2005). Missing data can be caused by a participant’s refusal to answer certain questions, an insufficient approach to data collection, or the inability of a researcher to identify subgroups within the population (Borgatti et al., 2013). While inaccuracies in data are possible, the pattern of connections are unlikely to be affected unless there were underlying biases in the way that the data were recorded/collected (Kao et al., 2006). For example, biases may be expected if data were only recorded for highly connected individuals or facilities, which would overestimate the connectivity within the population. Furthermore, inaccuracies occurring from data collection would likely be due to underreporting or misreporting (rather than over-reporting), which would therefore underestimate the true connectivity within the population (Kao et al., 2006).

1.4 Mathematical modeling and simulation

Mathematical models are methodological tools used to describe the structure and behaviour of a system of objects (Vynnycky and White, 2010). In epidemiological research, models can provide insight into population-level dynamics in situations where experimental or observational studies would not be feasible (Vynnycky and White, 2010). Mathematical models of disease transmission can describe disease spread in a population while incorporating specific host or pathogen-related factors (Mishra et al., 2011). In addition, they can be used to estimate key parameters of disease spread, highlight gaps in the available data, and determine the effectiveness of interventions that may not be practical to implement without stronger evidence (Mishra et al., 2011).

Models have been previously used in equine populations to study the disease dynamics of equine influenza (Glass et al., 2002; Satou and Nishiura, 2006; Daly et al., 2013), to characterize
its transmission (Park et al., 2009; Hughes et al., 2012), and to evaluate disease control strategies during an outbreak (de la Rua-Domenech et al., 2000; Park et al., 2003; Baguelin et al., 2010; Perkins et al., 2011). While other equine pathogens have been described using mathematical modeling (e.g., African horse sickness (de Vos et al., 2012) and equine infectious anemia (Hayama et al., 2012)), researchers have focused on equine influenza due to its well-characterized natural history, excellent challenge study data, and economic significance (Park et al., 2004; Gildea et al., 2011; Daly et al., 2013; Landolt, 2014).

1.4.1 Simplifying assumptions

Even the most complex models must make simplifying assumptions in order to approximate the system of interest. While models are often created using data from the population/disease of interest, assumptions regarding disease parameters, population structure, or individual characteristics must be made in either the absence of data, or to achieve parsimony. Parsimonious models can describe the system of interest with as few parameters as possible, and thus avoid the development of an overly complex model (El-Sayed et al., 2012). Model development depends on a balance of accuracy, transparency, and flexibility (Christley et al., 2013). Accuracy represents the ability to incorporate data to represent or replicate real-life observations (Christley et al., 2013). Transparency includes understanding (and explicitly stating) the input parameters and the mechanisms controlling the behaviour of the model (Christley et al., 2013). Flexibility includes the ability of the model to change and adapt to new observations or data if they become available (Christley et al., 2013). The incorporation of available data can increase confidence in model outputs and decrease the number of assumptions that must be made. As all models will incorporate some level of assumptions and uncertainties, a
“good” model can be assessed by examining its usefulness. A useful model is one that is well-suited to its purpose (e.g., informing policy-making), and was developed under the principles of open communication and transparency (Christley et al., 2013). The commonly used simplifying assumptions of deterministic processes and homogeneous mixing are briefly discussed below.

Deterministic processes

Deterministic compartmental models are often described as representing the “average” behaviour of a system (Vynnycky and White, 2010). Model projections from deterministic models are invariable because the input parameters are fixed (Vynnycky and White, 2010). In contrast, a stochastic model includes elements that account for the variable nature of biological processes (Vynnycky and White, 2010). Stochastic models can incorporate randomness or variability within a system by parameterizing the model using probability distributions (Garner et al., 2011; Rosanowski et al., 2016). Furthermore, this randomness can be considered at the individual-level (e.g., variability in transmission dynamics (Glass et al., 2002; Park et al., 2003)), or at the population-level (e.g., differences in contact patterns (Baguelin et al., 2010; Hayama et al., 2012)). Due to the incorporation of variable elements in stochastic models, a range of model projections are provided as outputs (Vynnycky and White, 2010).

Homogeneous mixing

Models of disease transmission have historically relied on the assumption of homogeneous mixing, which assumes that individuals within a population are equally likely to contact one another at random (Vynnycky and White, 2010). Homogeneous mixing can be further differentiated as frequency-dependent or density-dependent transmission. In frequency-
dependent transmission (also known as true mass-action), the contact rate does not change as the population size changes, and therefore disease transmission is independent of the population density (Vynnycky and White, 2010). In density-dependent transmission (also known as pseudo mass-action), the contact rate depends on the population density, so that disease transmission rates increase as the population density increases (Vynnycky and White, 2010). Models of equine disease have used frequency-dependent transmission to represent disease dynamics within the unique contact structure of horse populations (Glass et al., 2002; Park et al., 2003).

Homogeneous mixing is often used as an assumption due to the absence of data on more detailed contact or mixing patterns for a given population (Eames et al., 2015). Models that assume homogenous mixing are best used to approximate disease dynamics in a population with little variability in mixing patterns (Bansal et al., 2007). However, important differences in model projections arise when a homogenous-mixing model is used to describe disease dynamics in a population with an underlying contact structure. For instance, homogeneous-mixing models may overestimate the incidence and burden of disease in a population, as everyone is assumed to be equally likely to contact infectious individuals (Bansal et al., 2007). Furthermore, homogeneous mixing is often an oversimplification of the contact structure in livestock populations, as it does not adequately represent the observed mixing structure created by their movements. Livestock movement networks have been characterized as having disassortative mixing, where highly-connected facilities tend to be linked to less-connected facilities (Kiss et al., 2006; Duncan et al., 2014; Lentz et al., 2016). Without the explicit consideration of the network structure, a model might overestimate the contribution of these less-connected facilities to the projected disease spread. In addition, the impact of interventions tested in the model might be over- or under-estimated if the contact structure within a population is not considered, as the
impact of interventions targeted towards one group of facilities might depend on its connections to the others (Bansal et al., 2007).

1.4.2 Incorporating contact and mixing patterns

Because the transmission of directly transmitted pathogens between individuals is dependent on their contacts, incorporating more realistic contact patterns is an important step for improving the accuracy and reliability of models (Lanzas and Chen, 2015). While many approaches can be used to incorporate contact patterns (e.g., contact matrices and metapopulation models), the representation of contact patterns through a combination of network analysis and agent-based models is briefly discussed below.

Networks

Empirical network data can be incorporated into a simulation model to describe the connections between different individuals and/or groups of individuals. Options to describe contacts in a model include: 1) specifying the probability of contacts forming between two groups of individuals (Hayama et al., 2012; Gates and Woolhouse, 2015); 2) defining contact rates calculated directly from empirical data (Wallinga et al., 2006; Mossong et al., 2008; Salathé et al., 2010); and 3) explicitly representing the observed network structure in the model (Tinsley et al., 2012; Lebl et al., 2016; Arruda et al., 2017). A limitation of using empirical network data for model development is that the available data may not represent contacts that have actually led to disease transmission (Eames et al., 2015). Therefore, the interpretation of potential disease outcomes based on previously collected network data should be done with some caution, as differences in the observed contact patterns might be expected if a disease was actually present.
(Eames et al., 2015). For instance, farmers may modify their behaviour in response to policy
decisions prior to or following an outbreak, which has important implications for estimating
disease outcomes from previously described livestock movement networks (Vernon and Keeling,
2012; Gates et al., 2013).

Agent-based models

Agent-based models describe autonomous "agents" (i.e., individual entities) in a
population, and can define the behaviour and interactions of the agents in their environment
(Lanzas and Chen, 2015). Agent-based models can be used to incorporate a high level of
heterogeneity in a population, including variability in susceptibility, infectiousness, contact
patterns, and spatial location (Lanzas and Chen, 2015). In addition, they can describe individual-
level characteristics (e.g., age, sex, and vaccination status) to incorporate important sources of
biological variability in the model (Grimm et al., 2006). While agent-based models allow a high
level of heterogeneity (and therefore, a high level of complexity), limitations include difficulties
in collecting detailed data, analyzing and validating the model, and computational demands
(Lanzas and Chen, 2015).

1.4.3 Applications to disease prevention and control

Mathematical models can be used to inform policy decisions, including those related to
the development of outbreak prevention, detection, and response strategies (McNab et al., 2011).
When models are used to inform evidence-based decision making, it is imperative that
researchers are transparent regarding their strengths and limitations. Model outcomes should not
be regarded as future predictions, but should instead be used to fully examine the range of
possible outcomes, and to use the uncertainty around those outcomes to prepare for future situations (Christley et al., 2013). Models have been used to examine important questions related to equine disease prevention and control. For instance, Park et al. (2003) used a stochastic model of equine influenza to assess whether the recommended vaccination policy in the UK would be effective in preventing an outbreak. Baguelin et al. (2010) used a metapopulation model to assess the spread of equine influenza between equine training yards in the UK to evaluate potential control measures, supporting the use of reactive blanket vaccination (i.e., mass vaccination in the face of an outbreak). Nishiura and Satou (2010) used a modeling approach to determine the effectiveness of infection control interventions, such as movement restrictions, isolation, and quarantine, during an equine influenza outbreak. In exploring the potential for the spread of equine infectious anemia due to horse movements, Hayama et al. (2012) used modeling to determine effective surveillance strategies for detecting the disease. These examples highlight the use of models to determine effective disease prevention and control strategies in equine populations, including their potential use to inform policy decisions surrounding the implementation of these strategies.

1.5 Equine influenza

1.5.1 Etiology, clinical signs, and diagnosis

Equine influenza (EI) is caused by two subtypes of the equine influenza A virus (EIV), H7N7 and H3N8 (Timoney, 1996). The H7N7 subtype has not been isolated from horse populations since 1979, and thus the H3N8 subtype has been associated with outbreaks over the past 20 to 30 years (Cullinane et al., 2010; Daly et al., 2013). EIV is highly infectious and can result in 100% morbidity in a susceptible population (Dhand and Sergeant, 2011; Cullinane and...
Mortality due to EIV infection is rare (Landolt, 2014), but can occur due to secondary bacterial complications following EIV infection (Timoney, 1996).

After an incubation period of 1 to 2 days (Timoney, 1996), horses infected with EIV develop clinical signs including pyrexia, nasal discharge, and cough (Dups et al., 2011). A case definition of EI often consists of the presence of these three clinical signs; however, they do not always present at the same time in all horses (Dups et al., 2011). Other clinical signs of EI include depression, anorexia, and impairment of athletic performance (Timoney, 1996). The severity of clinical signs and the likelihood of adverse outcomes depends on the age and immune status of the horse (Timoney, 1996). Horses normally recover from EIV infection after 2 weeks, and there is currently no evidence of viral persistence or a carrier state in recovered horses (Timoney, 1996; Cullinane et al., 2010).

While a presumptive diagnosis of EI is normally made through examination of clinical signs, a definitive diagnosis can be made using diagnostic tests (Cullinane and Newton, 2013). Common diagnostic tests include enzyme-linked immunosorbent assay (ELISA), reverse transcription polymerase chain reaction (RT-PCR), and real-time quantitative reverse transcription polymerase chain reaction (real-time qRT-PCR) (Galvin et al., 2014). Treatment of EI usually consists of supportive care and reduced physical activity (i.e., reduced training intensity), and rest is suggested until clinical signs subside (Cullinane and Newton, 2013).

1.5.2 EIV transmission

Infected horses begin to shed EIV in nasal discharge within 24 to 48 hours of infection, and can continue to shed the virus for 5 - 8 days (Park et al., 2003; Paillot et al., 2013; Landolt, 2014). Direct transmission of EIV occurs through close contact with aerosolized respiratory
droplets, and indirect transmission can occur through contact with contaminated equipment, food/water, vehicles, and the hands/clothing of equine facility staff (Timoney, 1996; Guthrie et al., 1999). It is possible for EIV to remain viable for multiple days on contaminated surfaces, depending on the environmental conditions, such as temperature and humidity (Landolt, 2014). In addition, it has been reported that transmission via aerosolized respiratory droplets can occur over distances greater than 32 m (Timoney, 1996). During the 2007 Australian EI outbreak, there was suspected airborne spread of EIV between facilities located 1 to 1.5 km away from each other (Moloney, 2011).

1.5.3 Epidemiology

While EI is endemic in several countries and can occur during any season, outbreaks are most common during times of frequent travel and high turnover in equine facilities (Timoney, 1996; Landolt, 2014). Furthermore, the risk of an outbreak increases during periods with higher numbers of scheduled races, sales, shows, or training events, due to the opportunity for horses from multiple facilities to come into close contact with one another (Timoney, 1996; Cullinane and Newton, 2013). Identified risk factors for EIV infection include inadequate vaccination (e.g. low vaccine coverage levels in a facility or poor response to vaccination), frequent movements on/off the facility, and age (Gildea et al., 2011).

There have been few published reports of EI outbreaks in Ontario. In a study of Standardbred horses at three racetracks between 1973 – 1975, several EI outbreaks occurred annually in late winter and/or spring seasons (Sherman et al., 1979). These time periods corresponded to times when there was a higher proportion of young horses in the population (Sherman et al., 1979). Between December 1987 and July 1988, there were 29 reported EI
outbreaks in Ontario (Carman et al., 1997), and from September 2003 to November 2005, there were 23 reported EI outbreaks (Diaz-Mendez et al., 2010). From the 115 horses sampled during the most recently reported period of outbreaks (September 2003 to November 2005), 41 horses (36%) had been vaccinated for EI at least once during the previous year, while 44% were unvaccinated, and 20% had an unknown vaccine history (Diaz-Mendez et al., 2010).

1.5.4 Vaccination and immunity

In Canada, vaccination for EI is recommended, but not required (Ontario Ministry of Agriculture Food and Rural Affairs, 2013). Vaccination is recommended for horses at higher risk of exposure to infection, such as younger and older horses, horses used for breeding purposes, and horses that travel frequently (Ontario Ministry of Agriculture Food and Rural Affairs, 2013). There are two types of EI vaccines currently used in Canada: the killed-virus vaccine, and the modified live virus (MLV) intranasal vaccine (Ontario Ministry of Agriculture Food and Rural Affairs, 2013). Using the killed-virus vaccine, it is recommended that foals receive a series of 3 immunizations beginning at 6 months of age, with the first two immunizations administered 4 – 6 weeks apart, and the third administered when the foal is between 10 and 12 months of age (American Association of Equine Practitioners, n.d.; Ontario Ministry of Agriculture Food and Rural Affairs, 2013). Foals born to previously vaccinated mares will be protected through maternally-derived antibodies for three to six months (Cullinane and Newton, 2013), and therefore do not need to be vaccinated before 6 months of age (Landolt, 2014). For adult horses, it is recommended that horses be immunized every 3 – 12 months, depending on their age and risk of potential exposure (American Association of Equine Practitioners, n.d.; Ontario Ministry of Agriculture Food and Rural Affairs, 2013). Using the MLV intranasal vaccine, it is
recommended that foals be immunized using a single dose at 6 to 7 months of age, and then
given a second dose at 11 to 12 months of age (American Association of Equine Practitioners,
n.d.). Adult horses should be revaccinated with the MLV intranasal vaccine at 6-month intervals
(American Association of Equine Practitioners, n.d.; Ontario Ministry of Agriculture Food and
Rural Affairs, 2013).

While vaccination is often referred to as the “cornerstone” of an infection control
program, variations in immunological response, vaccination regimens, and duration of immunity
can impact its effectiveness (Paillot, 2014; Weese, 2014). Vaccination can offer two levels of
protection against EIV: 1) virological protection, defined as protection against transmitting and
becoming infected with EIV; and 2) clinical protection (commonly referred to as partial
protection), defined as protection against demonstrating clinical signs, but still capable of
becoming infected with and transmitting EIV (Paillot et al., 2006). In general, vaccination for EI
reduces the appearance of clinical signs (Gildea et al., 2013), decreases the probability of
becoming infectious (Park et al., 2003) and reduces the period of infectiousness (Park et al.,
2003; Kannegieter et al., 2011; Paillot, 2014). Vaccination may also impact the sensitivity of
outbreak detection within a facility, as a presumptive EI diagnosis using clinical signs may not
be possible in a population of vaccinated horses (Happold and Rubira, 2011).

Both subclinical infection in vaccinated horses and the variable duration of immunity
provided by vaccination present challenges for preventing and controlling EI spread. During
investigations of several EI outbreaks in Ireland in 2010 – 2012, subclinical infection was
identified in 50% (6/12) of known vaccinated horses (Gildea et al., 2013). In addition to
subclinical infection, perceived vaccine failure can occur due to a combination of variability in
vaccine effectiveness, poor immune response to vaccination, and antigenic drift (Newton et al.,
Furthermore, field investigations have demonstrated that the duration of immunity provided by the vaccine is short, and thus vaccines should be administered in 4- to 6-month intervals to maintain sufficient protection against infection (Cullinane and Newton, 2013). Lastly, a horse can experience a reduced or absent immunological response to vaccination, which can lead to the false belief that a horse is adequately protected against infection after vaccination (Paillot, 2014).

1.6 Thesis overview and objectives

The Canadian equine industry plays an important role in the Canadian economy, with a contribution of approximately $19 billion CAD in 2010 (Equine Canada, 2010). The industry consists of a diverse group of horses, ranging from competitors in the racing industry to companion animals. Given the high variability of the usages and ownership of horses in Ontario, there is a significant gap in the demographic knowledge of the population. In particular, there are existing questions surrounding the distribution of horse characteristics, the use of biosecurity and infection control practices, and potential horse contact patterns. Addressing these knowledge gaps can generate new evidence to help improve disease prevention and control strategies that will benefit the health and well-being of Ontario horses.

The overarching objective of this thesis was to examine the potential for disease spread within the Ontario equine population to inform and recommend evidence-based disease control strategies. This objective was addressed using network analysis and agent-based modeling strategies, while using equine influenza as an exemplar to describe the potential for disease spread in the population. This thesis is subdivided into six chapters. Chapter One includes a detailed description of the significance of disease outbreaks in horse populations, and methods to
evaluate the risk of disease introduction and spread. Chapters Two to Five address the following specific research objectives:

1. Demonstrate the importance of sustained infection prevention and control strategies during a simulated equine influenza outbreak in a hypothetical equine facility (Chapter 2);

2. Describe the potential for disease spread in the contact network formed as horses attend a single equestrian show in Ontario, Canada (Chapter 3);

3. Evaluate the effectiveness of vaccination and quarantine strategies during a simulated equine influenza outbreak in a network of horses formed by attending a single equestrian show in Ontario, Canada (Chapter 4);

4. Describe the demographics and movement patterns of horses enrolled in a longitudinal study in Ontario, Canada to identify the extent of connectedness of horses and facilities in the equine population (Chapter 5).

Lastly, Chapter Six presents a summary of the main results, and recommendations for future directions.
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CHAPTER TWO

Using a computer simulation model to examine the impact of biosecurity measures during a facility-level equine influenza outbreak

*In press at The Canadian Journal of Veterinary Research, August 2017*

2.1 Abstract

On-farm biosecurity measures are an important part of a control plan to minimize the introduction and spread of infectious diseases, such as equine influenza, in an equine facility. However, the efficacy of biosecurity measures can be challenging to evaluate under field conditions in the absence of an ongoing outbreak. We used an agent-based simulation model to describe the impact of 1) preventive vaccination, 2) reduced horse-to-horse contact, and 3) a combination of vaccination and reduced contact on the projected attack rate of a simulated equine influenza outbreak in a facility. The results demonstrate that the most effective intervention was a combination of a high proportion of recently vaccinated horses and a substantial reduction in horse-to-horse contact once equine influenza had been identified in the facility. This study highlights the importance of compliance when implementing biosecurity measures, such as facility-level infection control practices, on horse farms.

2.2 Introduction

Equine influenza (EI) is a respiratory disease caused by an influenza A virus (equine influenza virus (EIV)) and is common in equine populations worldwide (Timoney, 1996; Cullinane et al., 2010). Clinical signs of EI include fever, depression, nasal discharge, and coughing (Timoney, 1996), and results in impairment of athletic performance (Cullinane and
Direct transmission of EIV occurs through close contact with aerosolized respiratory droplets, and indirect transmission can occur through contact with contaminated equipment, food/water, vehicles, and the hands/clothing of humans (Timoney, 1996; Guthrie et al., 1999). The highly contagious nature and ability of EIV to spread rapidly in susceptible populations contributes to its economic importance at the regional, national, and international level (Cullinane et al., 2010).

The potential impact of EI within an equine facility can be minimized through the implementation of infection prevention and control measures. Prevention measures, such as quarantine after travel, stabling in well-ventilated facilities, and vaccination, are used to prevent the establishment of EI (Firestone et al., 2011; Gildea et al., 2011; Weese, 2014). While vaccination for EI is mandatory in some populations (Cullinane et al., 2010), it is not mandatory in Canada (Ontario Ministry of Agriculture Food and Rural Affairs, 2013). However, it is recommended for horses at higher risk of exposure to infection, such as in young and older horses, breeding horses, and those that travel frequently (American Association of Equine Practitioners, n.d.). While vaccination may offer short-term immunity, variations in immunological response, vaccination regimens, and duration of immunity affect population-level disease dynamics (Elton and Bryant, 2011; Weese, 2014). Other biosecurity measures, such as quarantine after travel, reducing contact between horses, and infection control strategies implemented by equine facility staff (e.g., hand-washing) should be used in addition to vaccination to minimize the risk of EI introduction and subsequent spread (Firestone et al., 2011; Gildea et al., 2011; Weese, 2014).

The successful implementation of biosecurity and infection control measures relies on the compliance of horse owners and equine facility staff. In the United States, a survey of horse
owners revealed that 80% of respondents either did not have or were unfamiliar with the biosecurity measures used at their horses’ facilities (Vanderman et al., 2009). Similarly, a survey of horse facilities in New Zealand demonstrated that the general usage of biosecurity measures at the facilities would be insufficient to prevent disease introduction (Rosanowski et al., 2012). The lack of awareness regarding the benefits of biosecurity and infection control measures suggests that alternate strategies are required to demonstrate their importance. Furthermore, quantifying the effects of biosecurity and infection control measures can strengthen the existing recommendations for the Canadian equine industry (Canadian Food Inspection Agency, 2016).

A computer simulation model is a tool that can synthesize knowledge from the peer-reviewed literature to capture the expected transmission dynamics of a pathogen within an average population without the use of clinical trials (Mishra et al., 2011). Models can provide critical insight into population-level effectiveness for interventions that may not be practical or cost-effective to implement without stronger evidence (Mishra et al., 2011). Key features of EI outbreaks have previously been described using mathematical models, such as an estimation of the basic reproductive number ($R_0$) (Glass et al., 2002; Satou and Nishiura, 2006), an evaluation of disease control strategies during an outbreak (de la Rua-Domenech et al., 2000; Garner et al., 2011; Perkins et al., 2011), and the optimization of recommended vaccination strategies (Park et al., 2003; Rosanowski et al., 2016). However, the previous studies have focused on disease control in exotic outbreak situations or in specific populations of horses (e.g., Thoroughbred racehorses in training).

The objective of this study was to utilize a computer simulation model to describe the impact of biosecurity and infection control measures during an EI outbreak within a simulated equine facility. This study focused on the effect of 1) increased initial facility-level vaccine
coverage prior to EI introduction, 2) reduced horse-to-horse contact following EI identification, and 3) a combination of increased vaccine coverage and reduced horse-to-horse contact. We hypothesized that implementing increased vaccine coverage before the outbreak and reduced horse-to-horse contact during the outbreak would greatly minimize the extent of the outbreak compared to either intervention alone.

2.3 Materials and methods

2.3.1 Model description

A stochastic agent-based model was constructed using Anylogic 7.1.2 (XJ Technologies, St. Petersburg, Russia) and was parameterized using data from the peer-reviewed literature (Table 2.1). Agent-based models describe individual “agents” in a population to account for biological heterogeneity and potential differences in behaviour. An agent-based model was chosen because we could explicitly describe the vaccination status of each horse. Specifically, we could determine the vaccination status and associated time since vaccination for each horse to account for individual-level heterogeneity in waning immunity following vaccination.

2.3.2 Population structure

We generated a synthetic population of 100 horses housed within a single equine facility. Since we were interested in examining short-term disease dynamics following a disease introduction event, we assumed the facility was a closed population with no births or deaths, and no movements in or out of the facility (as might be expected once an EI outbreak was identified). Individual horses were assigned to distinct age categories of yearlings (<2 years old, 35% of the population) and non-yearlings (≥2 years old, 65% of the population) to account for differences in
vaccine coverage between young and adult horses. The proportion of horses in each age category was chosen to capture the observation that an average equine facility has a higher proportion of non-yearlings than yearlings (T. O’Sullivan, personal communication).

### 2.3.3 Calibration

Model calibration was conducted to estimate the best fit contact rate parameter from an EI outbreak reported in the literature. The contact rate was defined as the number of horses that a single horse adequately contacts per day (i.e., a close proximity contact that would be suitable for EIV transmission) (Vynnycky and White, 2010). We assumed that contact was homogenous and all horses had an equal probability of randomly contacting one another. Furthermore, only the effects of EIV transmission via direct horse-to-horse contact were considered. Data from Morton et al. (2011) were used for model calibration. Morton et al. (2011) described a closed population of susceptible horses during the 2007 EI outbreak in Queensland, Australia. Our model was calibrated by varying the contact rate across a wide range of realistic values and determining the parameter value that provided the best model fit to the observed outbreak data (Morton et al., 2011) using least squares estimation.

In order to accurately compare the two populations, the outbreak curve in Morton et al. (2011) was converted to the number of new cases per day divided by the total population size, which was then multiplied by 100. Vaccination (and waning immunity) was not included as a compartment in the calibration model, and all horses were treated as susceptible during the calibration process. The calibration experiment was run for 1000 iterations to account for stochasticity in the disease initialization (i.e., introduction of the infectious horse) between iterations.
2.3.4 Vaccination and waning immunity

We assumed that 50% of yearlings and 70% of non-yearlings were vaccinated at the beginning of the simulation, corresponding to an initial facility-level vaccine coverage of 63% (Figure 2.1). Since we were interested in observing the effect of increasing the initial vaccine coverage, we assumed these proportions would represent a scenario with a moderate level of initial vaccine coverage, with yearlings having lower vaccine coverage than non-yearlings. As age was used to determine the proportion of vaccinated horses within each category, aging between categories was not considered in the model because horses were not vaccinated during the outbreak. We assumed that vaccination in the facility was synchronized for all horses and occurred prior to the start of the model, and the impact of revaccination during the model was not considered. In addition, we assumed that vaccinated horses had virological protection, which was defined as protection against transmitting and becoming infected with EIV. While research has demonstrated that previously vaccinated horses have a reduced probability of becoming infectious (Park et al., 2003) and a reduced period of infectiousness (Park et al., 2003; Kannegieter et al., 2011; Paillot, 2014), we assumed that the contribution of partially vaccinated horses to the force of infection would be negligible in our small population of horses. Furthermore, we did not consider the effect of a mismatched vaccine due to differences between the vaccine strain and the circulating EIV strain. For these reasons, we assumed that vaccinated horses could not transmit or become infected with EIV.

Stochasticity in the model was introduced using a triangular distribution to represent waning immunity following vaccination (Table 2.1). This distribution described the time at which horses in the vaccinated compartment returned to the susceptible compartment as their vaccine-induced immunity waned over time. Assumptions about the waning immunity
distribution in the model were informed using results from Newton et al. (2000). The immune response to EIV infection leads to antibody production that is adequate for virological protection for a short period of time post-vaccination, after which individual-level variability in the duration of virological protection is expected (Newton et al., 2000). In the model, all vaccinated horses were considered to have virological protection for at least 51 days, and potentially as long as 180 days. After 51 days, horses began to lose immunity at a rate defined by the waning immunity distribution and re-entered the susceptible compartment. This meant that vaccinated horses could re-enter the susceptible compartment at any point between 51 and 180 days, but the majority did so at the midpoint between these time points (116 days). Although waning immunity also exists following natural infection with EIV, it was not included in the model structure because the period of waning immunity following natural infection is longer than the model duration (Paillot et al., 2006).

2.3.5 EI introduction

Three independent model scenarios were chosen to represent different levels of risk in a population as vaccine-induced immunity wanes over time. In the “low-risk scenario”, one infectious horse was introduced 1 month after vaccination, when vaccinated horses should be protected from infection. In the “medium-risk scenario”, one infectious horse was introduced 3 months after vaccination, during a period of time when vaccine-induced immunity would begin to wane, and thus a small proportion of previously vaccinated horses would become susceptible. Lastly, in the “high-risk scenario”, one infectious horse was introduced 4 months after vaccination, at a time when most previously vaccinated horses in the population would be susceptible to infection due to waning immunity. One time-step represented one day, and the
model was run for 180 days.

The EI disease process followed a “susceptible-exposed-infectious-recovered” design with a vaccinated compartment (SEIRV) (Figure 2.1). Each horse in the population could only be in one compartment at any time during the simulation, and the transitions between each compartment were defined according to the parameters in Table 2.1. Unvaccinated horses began the simulation in the susceptible compartment. Transmission of EIV between an infected horse and a susceptible horse occurred through direct contact (at a rate determined through the calibration experiment), and was a function of both the contact rate and the probability of transmission given an adequate contact. Newly infected horses remained in the exposed compartment for the duration of the latent period (Table 2.1), and could not transmit EIV while in this compartment. Horses in the infectious compartment were assumed to be equally infectious, and remained infectious for the duration of the infectious period (Table 2.1).

2.3.6 Model outcomes

Each scenario was run for 1000 iterations to calculate a range of possible clinical attack rates in the absence of any additional interventions (referred to as the base case scenarios). The clinical attack rate was defined as the total number of infected horses at the end of the simulation run divided by the size of the population (100 horses). The secondary outcome of interest was the outbreak duration, which was defined as the time when the outbreak ended. Model outcomes were summarized using the statistical software packages Stata (StataCorp. 2013. Stata Statistical Software: Release 14. College Station, TX: StataCorp LP), and R (R Core Team. 2016. R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing).
2.3.7 Interventions

Three intervention strategies were tested in each scenario: 1) increases in the initial facility-level vaccine coverage to 73%, 83%, and 93% prior to the outbreak, 2) decreases in the contact rate by 25%, 50%, and 75% during the outbreak (referred to as a reduction in horse-to-horse contact), and 3) a combination of increased vaccine coverage and decreased horse-to-horse contact (referred to as the bundled intervention), further described in Table 2.2. An increase in the initial facility-level vaccine coverage was directly proportional to the proportion of horses that would have vaccine-induced immunity at the beginning of the model. For example, at 93% vaccine coverage, 93% of the horses in the facility would have vaccine-induced immunity at the start of the simulation. We assumed that a reduction in horse-to-horse contact would take one day to implement after the identification of a single case, and therefore horse-to-horse contact was reduced the day after the infectious horse was introduced into the facility. Each intervention scenario was run for 1000 iterations.

2.3.8 Sensitivity analysis

Univariate sensitivity analyses were conducted to determine the impact of assumptions regarding the infectious period and the waning immunity distribution. Each parameter was varied independently for 1000 iterations per value (Table 2.3). The infectious period was varied between 3.0 days and 7.0 days, consistent with the previously reported EI shedding period (Mumford et al., 1994). The waning immunity distribution was varied to determine the impact of immunity waning 30 days earlier than expected and 30 days later than expected.
2.4 Results

2.4.1 Model calibration and base case outcomes

Calibration to outbreak data (Morton et al., 2011) resulted in a best-fit contact rate parameter of 4.86 contacts per day, which was used for all examined model scenarios. In the low-risk base case scenario, the average clinical attack rate was 38% (SD = 5%, range = 21 – 58%) and the average outbreak duration was 15 days (SD = 6 days, range = 6 – 23 days). In the medium-risk base case scenario, the average clinical attack rate was 38% (SD = 5%, range = 25 – 53%) and the average outbreak duration was 15 days (SD = 2 days, range = 6 – 26 days). In the high-risk base case scenario, the average clinical attack rate was 47% (SD = 23%, range = 22 – 100%) and the average outbreak duration was 15 days (SD = 2 days, range = 11 – 30 days).

2.4.2 Interventions

In the low-risk scenario, increasing the initial facility-level vaccine coverage resulted in a decreased clinical attack rate (Figure 2.2) and a shorter outbreak duration (Figure 2.3). At 93% vaccine coverage, the average clinical attack rate decreased to 6% (SD = 4%, range = 1 – 16%), and the average outbreak duration decreased to 14 days (SD = 6 days, range = 6 – 33 days). Compared to the low-risk base case scenario, there was increased variability between simulation runs when horse-to-horse contact was reduced by 75% (average clinical attack rate = 34%, SD = 7%, range = 1 – 53%) (Figure 2.2). Reducing horse-to-horse contact also resulted in longer outbreak durations. When horse-to-horse contact was reduced by 75%, the average outbreak duration was 25 days (SD = 5 days, range = 6 – 53 days). The bundled interventions (described in Table 2.3) resulted in decreased variability between simulation runs, lower average clinical attack rates, and shorter outbreak durations compared to either intervention alone. Bundle 6 (a
combination of 93% initial vaccine coverage and a 75% reduction in horse-to-horse contact) resulted in an average clinical attack rate of 3% (SD = 2%, range = 1 – 12%) and an average outbreak duration of 9 days (SD = 4 days; range = 6 – 31 days).

The medium-risk scenario resulted in clinical attack rates with increased variability between simulation runs (Figure 2.2). At 93% vaccine coverage, the average clinical attack rate was 7% (SD = 8%, range = 1 – 99%) and the average outbreak duration was 15 days (SD = 9 days, range = 6 – 127 days). When horse-to-horse contact was reduced by 75%, the resulting average clinical attack rate was lower than the medium-risk base case scenario (34%, SD = 7%, range = 1 – 71%) and the average outbreak duration increased (26 days, SD = 7 days, range = 6 – 100 days). Bundle 6 resulted in the lowest average clinical attack rate (3%, SD = 2%, range = 1 – 13%) and the shortest average outbreak duration (9 days, SD = 4 days, range = 6 – 34 days).

Interventions applied in the high-risk scenario resulted in clinical attack rates with bimodal distributions (meaning that the expected outbreaks could be small or could be much larger than expected) and increased variability between simulation runs (Figure 2.2). At 93% vaccine coverage, the average clinical attack rate was lower than in the high-risk base case scenario (19%, SD = 34%, range = 1 – 100%) and the average outbreak duration was shorter (14 days, SD = 6 days, range = 6 – 38 days). As horse-to-horse contact was reduced, there was no change in either the average clinical attack rate (Figure 2.2) or the average outbreak duration (15 days, SD = 2 days, range = 12 – 31 days). Out of the bundled interventions, bundle 6 resulted in the lowest average clinical attack rate (18%, SD = 32%, range = 1 – 100%) and the shortest outbreak duration (14 days, SD = 6 days, range = 6 – 36 days) compared to the high-risk base case scenario. However, the average clinical attack rate in the high-risk scenario was still greater than the average clinical attack rate in both the low- and medium-risk scenarios when bundle 6
was applied (18% in the high-risk scenario vs. 3% in the low-risk and medium-risk scenarios).

2.4.3 Sensitivity analysis

The results of the sensitivity analyses are presented in Table 2.3. Varying the waning immunity distribution had the greatest impact on the average clinical attack rate in the medium- and high-risk scenarios. In the medium-risk scenario, immunity waning earlier than expected increased the average clinical attack rate to 45% (SD = 21%, range = 24 – 100%), but there was no change when immunity waned later than expected. In the high-risk scenario, the average clinical attack rate increased to 68% (SD = 32%, range = 24 – 100%) when immunity waned earlier, and decreased to 38% (SD = 6%, range = 1 – 100%) when immunity waned later.

2.5 Discussion

This computer simulation study has demonstrated that implementing a combination of high facility-level vaccine coverage prior to an EI outbreak and a substantial reduction in horse-to-horse contact during an outbreak was the most effective strategy to minimize the impact of an EI outbreak in a facility. The results suggest that vaccination alone may be sufficient to minimize the extent of an outbreak, provided that horses in the facility have been recently vaccinated (i.e., horses are not in the waning immunity phase). As vaccine-induced immunity starts to wane (as observed in the medium- and high-risk scenarios), the clinical attack rate becomes less predictable as the variability between simulation runs increases. In the high-risk scenario, all intervention strategies resulted in attack rates with bimodal distributions, demonstrating the uncertainty of their effect in a population that has not been recently vaccinated. If horses in the facility have not been recently vaccinated, reducing horse-to-horse contact is most useful for
slowing transmission (as implied by the longer outbreak durations), subsequently providing more
time to implement additional biosecurity and infection control measures. These results support
the recommendation of using a combination of multiple biosecurity and infection control
measures for disease prevention and control.

In the low- and medium-risk scenarios, increasing the initial facility-level vaccine
coverage had an important protective effect on EIV transmission. This finding supports previous
modeling studies that have contributed to evidence-based recommendations for increased
vaccine coverage in equine facilities (Park et al., 2003; Baguelin et al., 2010). Although
vaccination was effective in decreasing the average clinical attack rate in the medium- and high-
risk scenarios, there was increased variability between simulation runs as immunity waned over
time. The effect of waning immunity during an EI outbreak has been previously described in
field investigations in Ireland (Gildea et al., 2013). In these investigations, horses that had been
vaccinated 5 or more months prior to their exposure to EI became infected, during a time when
immunity would be expected (Gildea et al., 2013). The results of the current study support the
need for a safe, well-tolerated vaccine with long-lasting immunity, in addition to vaccination
strategies that shorten the period of time that horses in a population are susceptible.

As with any computer simulation, our model makes several simplifying assumptions.
There is currently little published data on the average size of equine facilities in Canada.
Unpublished data suggests that an average equine facility in Ontario, Canada boards 17 horses,
but ranges from 1 horse to over 100 horses. Therefore, the population size of 100 horses used in
this study might not be representative of all equine facilities, but would instead provide an
overview of the impact of biosecurity and infection control measures in a larger equine facility.
The model assumed that the vaccination regimen of horses in the facility was synchronized,
which may not be representative of all facilities. If vaccination within a facility is not synchronized, the model projections might not accurately represent the time points at which horses will have decreased virological protection (i.e., the low-, medium-, and high-risk scenarios would have different time points depending on the vaccination schedule implemented in the facility). Further research is warranted on the timing and frequency of vaccination in a facility to determine the appropriateness of the assumption of a synchronized vaccination schedule.

The assumption of a vaccine with 100% efficacy may be overly simplistic, and provides conservative estimates for model projections. The use of this assumption would potentially underestimate the true attack rate in a facility using a less efficacious vaccine. Similarly, the assumption that vaccinated horses could not become infected or transmit infection would underestimate the expected attack rate in the absence of this assumption. Lastly, the waning immunity distribution used in the model may vary depending on the type of vaccine product used and the individual immune status of the horse.

Future research is required to explore factors surrounding horse-to-horse contact within facilities, including alternatives to the homogeneous mixing assumption (e.g., describing within-facility contact patterns). While our model was well-calibrated to observed outbreak data (Morton et al., 2011), each outbreak may have its own transmission dynamics, including the potential for indirect transmission of EIV (Morton et al., 2011; Daly et al., 2013). Calibration of our model to observed outbreak data might overestimate the contact rate if a proportion of EI spread occurred through indirect transmission in the outbreak reported by Morton et al. (2011). Continued research on equine contact patterns would also provide insight into the real-life equivalence of reducing horse-to-horse contact by a certain percentage, and its feasibility in
Canadian equine facilities.

This study demonstrates the utility of computer simulation modeling in equine populations. Our findings support the continued vaccination of horses with an effective vaccine to counteract potential gaps in protection due to waning immunity. In addition, the results provide evidence-based recommendations that promote a combination of vaccination and reduced contact as an effective infection control practice. This model has the potential to be used for knowledge translation and transfer to inform veterinary practitioners and horse owners of the benefits of sustained biosecurity practices. Lastly, this study highlights future research opportunities for using computer simulation models in equine populations to inform effective disease prevention and control measures.

2.6 References


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### Tables

**Table 2.1.** Disease parameters used in the agent-based model of an equine influenza outbreak in a simulated equine facility.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact rate</td>
<td>4.86 contacts/day</td>
<td>Model calibration (Morton et al., 2011)</td>
</tr>
<tr>
<td>Probability of transmission given contact</td>
<td>1.00</td>
<td>(Park et al., 2003)</td>
</tr>
<tr>
<td>Latent period</td>
<td>1.25 days</td>
<td>(Glass et al., 2002)</td>
</tr>
<tr>
<td>Infectious period</td>
<td>5.5 days</td>
<td>(Glass et al., 2002)</td>
</tr>
<tr>
<td>Period of virological protection</td>
<td>50 days</td>
<td>(Newton et al., 2000)</td>
</tr>
<tr>
<td>Waning immunity following vaccination</td>
<td>Triangular distribution</td>
<td>(Newton et al., 2000)</td>
</tr>
<tr>
<td></td>
<td>(Min. 51 days; max. 180 days; mode 116 days).</td>
<td></td>
</tr>
</tbody>
</table>
Table 2.2. Descriptions of intervention strategies tested in the agent-based model of an equine influenza outbreak in a simulated equine facility.

<table>
<thead>
<tr>
<th>Intervention</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase initial vaccine coverage</td>
<td>Increased initial facility-level vaccine coverage from the base case value (63%) to 93% in 10% increments prior to the introduction of the infected horse.</td>
</tr>
<tr>
<td>Decrease horse-to-horse contact</td>
<td>Reduction in horse-to-horse contact by 25%, 50%, and 75% starting on the day following the introduction of the infected horse and continuing throughout the duration of the outbreak.</td>
</tr>
<tr>
<td>Bundled intervention Bundle 1</td>
<td>Combination of 73% initial facility-level vaccine coverage and a 25% reduction in horse-to-horse contact.</td>
</tr>
<tr>
<td>Bundle 2</td>
<td>Combination of 73% initial facility-level vaccine coverage and a 75% reduction in horse-to-horse contact.</td>
</tr>
<tr>
<td>Bundle 3</td>
<td>Combination of 83% initial facility-level vaccine coverage and a 25% reduction in horse-to-horse contact.</td>
</tr>
<tr>
<td>Bundle 4</td>
<td>Combination of 83% initial facility-level vaccine coverage and a 75% reduction in horse-to-horse contact.</td>
</tr>
<tr>
<td>Bundle 5</td>
<td>Combination of 93% initial facility-level vaccine coverage and a 25% reduction in horse-to-horse contact.</td>
</tr>
<tr>
<td>Bundle 6</td>
<td>Combination of 93% initial facility-level vaccine coverage and a 75% reduction in horse-to-horse contact.</td>
</tr>
</tbody>
</table>
Table 2.3. Sensitivity analyses of the infectious period and the waning immunity distribution used in the agent-based model of an equine influenza outbreak in a simulated equine facility.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Low-risk</th>
<th>Medium-risk</th>
<th>High-risk</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>38 (6, 1 – 55)</td>
<td>37 (6, 1 – 100)</td>
<td>46 (22, 1 – 100)</td>
</tr>
<tr>
<td><strong>Infectious period</strong></td>
<td>Minimum 3.0 days</td>
<td>38 (5, 23 – 52)</td>
<td>38 (6, 22 – 100)</td>
<td>46 (22, 24 – 100)</td>
</tr>
<tr>
<td></td>
<td>Maximum 7.0 days</td>
<td>38 (5, 23 – 54)</td>
<td>38 (6, 22 – 100)</td>
<td>46 (22, 24 – 100)</td>
</tr>
<tr>
<td><strong>Waning immunity</strong></td>
<td>Early Triangular distribution</td>
<td>38 (5, 23 – 55)</td>
<td>45 (21, 24 – 100)</td>
<td>68 (32, 24 – 100)</td>
</tr>
<tr>
<td></td>
<td>Late Triangular distribution</td>
<td>38 (5, 23 – 52)</td>
<td>39 (5, 23 – 58)</td>
<td>38 (6, 1 – 100)</td>
</tr>
</tbody>
</table>

*a The infectious period was varied in increments of 0.5 between the minimum and maximum value.

*b Model-projected clinical attack rates only provided for minimum and maximum scenarios.

*c SD = standard deviation.
Figure 2.1. Schematic diagram of the agent-based model, including initial population conditions in the simulated equine facility and equine influenza infection.
Figure 2.2. Violin plots of the projected clinical attack rate in the low-risk, medium-risk, and high-risk scenarios after interventions were applied in the agent-based model. Intervention scenarios include increased initial facility-level vaccine coverage prior to the outbreak, reduced horse-to-horse contact during the outbreak, and bundled interventions. Bundles are a combination of increased initial vaccine coverage and reduced contact between horses (further described in Table 2.2). Each violin plot represents a kernel density estimation of the distribution of 1000 simulation runs.
**Figure 2.3.** Violin plots of the outbreak duration in the low-risk, medium-risk, and high-risk scenarios after interventions were applied in the agent-based model. Intervention scenarios include increased facility-level vaccine coverage prior to the outbreak, reduced horse-to-horse contact during the outbreak, and bundled interventions. Bundles are a combination of increased initial vaccine coverage and reduced contact between horses (further described in Table 2.2). Each violin plot represents a kernel density estimation of the distribution of 1000 simulation runs.
CHAPTER THREE

Descriptive and network analyses of the equine contact network at an equestrian show in Ontario, Canada and implications for disease spread

Published in BMC Veterinary Research (2017) 13:191.

3.1 Abstract

Identifying the contact structure within a population of horses attending a competition is an important element towards understanding the potential for the spread of equine pathogens as the horses subsequently travel from location to location. However, there is limited information in Ontario, Canada to quantify contact patterns of horses. The objective of this study was to describe the network of potential contacts associated with an equestrian show to determine how this network structure may influence potential disease transmission. This was a descriptive study of horses attending an equestrian show in southern Ontario, Canada on July 6 and 7, 2014. Horse show participants each completed a questionnaire about their horse, travel patterns, and infection control practices. Questionnaire responses were received from horse owners of 79.7% (55/69) of the horses attending the show. Owners reported that horses attending the show were vaccinated for diseases such as rabies, equine influenza, and equine herpesvirus. Owners demonstrated high compliance with most infection control practices by reporting reduced opportunities for direct and indirect contact while away from home. The two-mode undirected network consisted of 820 nodes (41 locations and 779 horses). Eight percent of nodes in the network represented horses attending the show, 87% of nodes represented horses not attending the show, but boarded at individual home facilities, and 5% represented locations. The median degree of a horse in the network was 33 (range: 1 – 105). Developing disease management strategies without the explicit
consideration of horses boarded at individual home facilities would underestimate the connectivity of horses in the population. The results of this study provide information that can be used by equestrian show organizers to configure event management in such a way that can limit the extent of potential disease spread.

3.2 Introduction

The globally expanding livestock industry has made the prevention and control of infectious diseases more challenging. Animal movements have been internationally recognized as a risk factor for disease introduction and spread, notably following outbreaks such as the 2001 foot-and-mouth disease outbreak in the United Kingdom (Ortiz-Pelaez et al., 2006) and the 2007 equine influenza outbreak in Australia (Bell and Drury-Klein, 2011). Opportunities for the introduction and spread of disease exist as animals move between locations due to the potential for contact with animals outside of their routine daily contacts (i.e., other animals at the same facility). An understanding of animal movement and contact patterns is essential to identify the risk of disease spread within a population and to determine intervention strategies in the event of an outbreak. The Canadian equine industry contributed more than $19 billion to the Canadian economy in 2010 (Equine Canada, 2010). Horses within the industry are highly mobile, travelling locally, regionally, and nationally to participate in show and sporting events. Previous studies have characterized animal contact patterns at these types of shows, including a network of sheep attending agricultural shows (Webb, 2006) and a network of donkeys attending equestrian shows (Finney et al., 2015). In recent years, disease outbreaks at equestrian shows have become more prevalent. Examples include the introduction and widespread transmission of equine influenza in Australia in 2007, which was thought to occur after the importation of an
infected horse for a competition (Kirkland et al., 2011; Moloney, 2011), and an outbreak of equine herpesvirus-1 in the USA in 2011, which occurred after horses gathered at a competitive event (Traub-Dargatz et al., 2013).

Epidemiological approaches that do not explicitly consider contact patterns may be insufficient to estimate the risk of disease spread within the equine population (Dubé et al., 2009; Firestone et al., 2011; Sánchez-Matamoros et al., 2013). Social network analysis is an approach that is generally used to explore and characterize the relationship between a group of individuals or locations (Dubé et al., 2009). In veterinary epidemiology, social network analysis has been previously used to characterize livestock contact and movement patterns to estimate the potential risk of disease spread (Dubé et al., 2010; Firestone et al., 2011; Hayama et al., 2012; Dorjee et al., 2013; Sánchez-Matamoros et al., 2013).

In some countries, the availability of a national database has allowed for full characterization of equine movement and contact networks (Sánchez-Matamoros et al., 2013). However, the current ability to trace equine contacts and travel patterns in Ontario is limited, and there is substantial variability in individual-level record keeping regarding these travel patterns (Equine Canada, 2010). The objective of this study was to describe the network of potential contacts associated with a single equestrian show in southern Ontario to determine how network structure may affect potential disease transmission.

### 3.3 Materials and methods

#### 3.3.1 Study location

This was a descriptive study of horses attending an equestrian show in Orangeville, Ontario, Canada on July 6 and 7, 2014. The equestrian show of interest was an Equine Canada
sanctioned two-day silver level dressage competition (Equestrian Canada, 2016). Upon entering the competition, participating riders could choose to have their horse stabled on-site for the duration of the show. The fairgrounds had two unique locations where participating horses could be stabled: the main barn and the coverall barn. Other participating horses were trailered in daily (ship-ins), meaning they did not stable at the facility overnight, but rather travelled to the fairgrounds and remained in a separate outdoor location (field parking area) until their warm up and/or competition time. For the purpose of this study, this location was referred to as the field.

3.3.2 Questionnaire and data collection

A questionnaire was developed using a three-stage process, which included design, pre-testing using personal interviews, and final distribution. For this study, the home facility was defined as the facility where a horse spent the majority of its time. The questionnaire contained 18 questions relating to 1) information about the competing horse (age, sex, stabling location, and vaccination status); 2) information about the horse’s home facility (geographic location, total number of horses boarded, number of owners that boarded horses at the facility, and presence of breeding mares, foals, and senior horses at the facility); 3) average number of incoming and outgoing horse movements from the home facility per month; 4) travel patterns of the horse six months prior to the show and six months following the show; and 5) the opportunities for contact to occur both at the home facility and while stabled away from home (direct nose-to-nose contact, sharing equipment, sharing cleaning tools, sharing water/feed, and sharing a wash rack) (Appendix II).

Participants were made aware of the research project and data collection activities prior to the show date through advertisement on the social media pages of the equestrian organization.
During the show, periodic announcements over the speaker and personal interactions with show participants aimed to increase awareness of the study. Owners, trainers, and/or riders were asked to complete the 2-page questionnaire on-site regarding the horse that they were responsible for at the show. Participants were eligible to complete the questionnaire if they were 18 years of age or older, had a horse present at the show, and were registered to compete. Only one questionnaire per horse was accepted, and duplicates were avoided by asking for the unique competition entry number of the horse. Participants could complete a questionnaire for more than one horse if they were responsible for several horses. Participants submitted their completed questionnaire in a locked box on-site, which was kept closed until the research team left the fairgrounds. Questionnaires were anonymous as no personally identifying information was collected. Information on the horses of non-responding owners, such as their stabling location, age, and sex, was collected from publically available competition entry data on the equestrian organization’s website.

The statistical software package Stata (StataCorp. 2013. Stata Statistical Software: Release 14. College Station, TX: StataCorp LP) was used for all descriptive analyses. Statistically significant differences (\(P\)-value < 0.05) were assessed between the proportion of participants that reported opportunities for contact at the home facility compared to opportunities for contact away from home using the Fisher’s exact test. Spearman’s correlation coefficient and the Wilcoxon rank-sum test were used to evaluate statistically significant differences between the estimated number of horse movements six months prior to the show and six months following the show by age and sex.
3.3.3 Network analysis

A two-mode undirected network was created to represent the relationships between horses and locations. The first mode consisted of individual horses, which included horses that were competing at the show (primary contacts) and horses stabled at the home facilities of those competing horses (secondary contacts). The second mode consisted of locations, which included areas at the fairgrounds and individual home facilities. Edges between a horse and a location represented the presence of the horse in that location. Horses were categorized by location through a question on the questionnaire that asked about its boarding location at the fairgrounds. Some horses at the fairgrounds boarded at the same home facility, and therefore multiple horses at the show could be connected to one home facility. Horses that attended the show but had owners that did not complete the questionnaire were included in the network, but were not connected to any home facility.

The two-mode network was projected as a one-mode network by creating a horse-by-location matrix and multiplying this matrix by its transpose. When plotted as a graph, the one-mode network provides a visual representation of the connections between individual horses based on co-boarding at the same locations, assuming that all horses in that location have the same potential for contact. By projecting as a one-mode network, the connections between individual horses could be described by calculating network measures. Edges in the one-mode network were unweighted, as information on the intensity and duration of horse-to-horse contact within each location was not collected. The networks were visualized using Gephi v. 0.8.1-beta (Bastian et al., 2009).

Descriptive network measures for the one-mode network were calculated in the statistical software R using the ‘igraph’ library (Csardi and Nepusz, 2006). These measures included:
density, which is the proportion of connections among horses in the network relative to the total number of possible connections (Dubé et al., 2009); diameter, which is the largest geodesic distance between any two horses in the network (Martínez-López et al., 2009); path length, which is the number of distinct steps between any two horses (Martínez-López et al., 2009); and clustering coefficient, which measures the proportion of horse connections that are also connected to one another (Dubé et al., 2009).

Measures of centrality were also calculated to provide an indication of the importance of a given horse based on how connected it is in the network (Dubé et al., 2009). In an undirected network, the degree is the number of connections of a horse (Dubé et al., 2009). Betweenness centrality estimates how often a horse is found on the shortest path between any two horses (Martínez-López et al., 2009). A higher betweenness score is assigned if the horse indirectly connects many other horse pairs. Closeness centrality estimates how closely connected a horse is to other horses in the network (Martínez-López et al., 2009). A high normalized closeness centrality score reflects a horse that has a short path distance to every other horse, thus being indirectly or directly reachable by other horses in the network (Borgatti et al., 2013). The Eigenvector centrality score measures the importance of a horse in the network by assigning its score relative to its connections to others, so that high-scoring neighbours of a horse will contribute more to its individual score (Borgatti et al., 2013).

3.4 Results

3.4.1 Horse demographics

Questionnaire responses were received from horse owners of 55 out of the 69 horses attending the show (response rate: 79.7%). The average age of a horse at the show was 9.6 years
(range 4 – 24 years). The majority of horses attending the show were geldings (33/55), followed by mares (21/55), and one stallion. Sixty-four percent (35/55) of participants had horses that were stabled overnight at the event; of those participants, 43% (15/35) were stabled in the barn and 57% (20/35) in the coverall. Sixty-nine percent (37/54) of participants stated there were other horses from their home facility participating at the same show. Of those participants, 73% (27/37) stated that these horses were stabled in neighbouring stalls, while 16% (6/37) did not provide information on the boarding location of the other horses.

3.4.2 Home facilities

Descriptions of participants’ home facilities are presented in Table 3.1. The home facilities of 55% of participants (30/55) were located less than 50 kilometres away from the show location (range 6 – 370 km) (Figure 3.1). The majority of participants (80%) came from home facilities that housed horses owned by four or more owners. The average number of horses boarded at individual home facilities was 22 (median = 12, range 2 – 85).

3.4.3 Horse movements

Descriptions of horse movements from participants’ home facilities are presented in Table 3.2. The estimated number of horses that entered a participant’s home facility per year (for reasons such as training, shows, new boarders, breeding, etc.) ranged from 0 to 500 (median = 4). There were no statistical differences between the median number of times a horse travelled relative to the show date depending on its sex (6-month period prior to the show date: mares and geldings, \( z = -0.62, P\text{-value} = 0.53 \); mares and stallions, \( z = 0.76, P\text{-value} = 0.45 \); geldings and stallions, \( z = 0.46, P\text{-value} = 0.64 \). 6-month period following the show date: mares and geldings,
z = 0.78, P-value = 0.43; mares and stallions, z = 0.25, P-value = 0.80; geldings and stallions, z = 0.56, P-value = 0.57.) In addition, there was no significant correlation between the number of times a horse travelled relative to the show date and its age (6-month period prior to the show date: rho = 0.22, P-value = 0.10; 6-month period following the show date: rho = -0.13, P-value = 0.37).

3.4.4 Infection control and biosecurity

Individuals reported a reduction in the opportunities for contact to occur between horses while away from their home facility (Figure 3.2). However, there were no statistically significant differences between the proportion of participants that reported opportunities for contact at the home facility compared to the proportion of participants that reported opportunities for contact away from home (direct nose-to-nose contact, P-value = 0.25; sharing equipment, P-value = 0.10; sharing cleaning tools, P-value = 0.49; sharing water/feed, P-value = 1.00; sharing a wash rack, P-value = 1.00). While most participants indicated that direct nose-to-nose contact of horses occurred both at their home facility and while away from home (76% and 22%, respectively), participants reported a reduction in sharing equipment, cleaning tools, and water/feed when they travelled away from home. Seven percent of participants indicated that there were no types of contact that occurred at the home facility, compared to 33% of participants that stated no types of contact occurred while away from home.

Owner-reported vaccine coverage levels in the past 12 months included equine influenza virus (96%, 50/52), rabies (90%, 47/52), strangles (60%, 31/52), West Nile virus (88%, 46/52), eastern equine encephalitis and western equine encephalitis (85%, 44/52), equine herpesvirus (73%, 38/52), and tetanus (83%, 43/52). Only one participant stated that their horse was
unvaccinated for all diseases listed, while 7% (4/54) were unsure of the vaccination status of their horse.

3.4.5 Network analysis

The two-mode network of horses attending the show consisted of 820 nodes (41 locations and 779 horses) and 834 edges (Figure 3.3). Five percent of nodes in the network represented locations: 4.6% (38/820) represented individual home facilities and 0.4% (3/820) represented the separate stabling or ship-in locations at the fairgrounds. Only 8% (69/820) of the nodes in the network represented horses that were competing at the show, while 87% (710/820) represented horses stabled at individual home facilities. When the two-mode network was projected as a one-mode network, there were 779 nodes (horses) and 16032 edges (Figure 3.4). Network measures calculated from the one-mode network are listed in Table 3.3.

The median (range) degree of the nodes in the one-mode network was 33 (1 – 105). The nodes with the smallest degree were secondary contacts at two separate home facilities where only those horses and the competing horses were boarded. The nodes with the highest degree corresponded to three competing horses that boarded at the same home facility, which housed 80 horses. The same three nodes also had the highest Eigenvector centrality scores. The node with the highest betweenness centrality and closeness centrality scores was a horse that was stabled in the coverall, but boarded at the same home facility as another competing horse that was shipped-in and remained in the field.
3.5 Discussion

This study has provided a description of horses and home facilities related to a single equestrian show in southern Ontario, Canada in July 2014. This study has also described the network of potential contacts associated with this show. The findings presented in this study contribute to a better understanding of the contact patterns of horses attending an equestrian show. The inclusion of the secondary contacts in the network demonstrated the high amount of connectivity beyond the horses that were present at the show, highlighting the importance of describing these contacts when estimating the risk of disease spread in the population.

The sampling method for this study was a convenience sample of horse owners/trainers/riders at the show, and therefore may not be representative of the general Ontario equine population. However, the high response rate for the questionnaire suggests that the network is fairly well characterized for horses associated with this particular show. Previous contact networks in veterinary medicine have been constructed using databases of animal movements (Christley and French, 2003; Sánchez-Matamoros et al., 2013) or information obtained through registries (Webb, 2005), however, such information is not available in Ontario. Simply using a complete list of registrants at the show would not have allowed for the detailed collection of data about individual home facilities, or the identification of secondary contacts at these home facilities.

Most horses were boarded at home facilities less than 50 kilometres away from the fairgrounds, suggesting that potential disease spread initiating at the show would have a higher probability of being contained in the local area due to the majority of contacts residing in close geographic proximity. Since only a small proportion of horses were boarded at locations farther away from the show location, wide geographic spread of a potential disease via horses travelling
back to their facilities would be less likely. The majority of horses residing in close geographic proximity to the show location could be explained by the equestrian sport of interest (dressage) and the type (silver level competition) of equestrian show being studied. In Canada, dressage has three competition levels that relate to the type of membership purchased: bronze, silver, and gold. Each level may attract a different group of competitors based on the competitiveness of their horse and if they wish to compete locally (bronze), provincially (silver), or nationally (gold) (Equestrian Canada, 2016). Differences in the contact network structure could be expected between different competition levels or equestrian sports. For instance, a network of horses that exclusively competed at the gold level might have more contacts over a wide geographic range. The potential difference in network structure between competition levels and equestrian sports is an area identified for future research.

The horses in this study were vaccinated for most equine diseases, and had an owner-reported vaccine coverage level that was much higher than previously reported for Ontario horses (Diaz-Mendez et al., 2010). The differences in vaccination coverage reported previously for Ontario horses may be attributed to the differences in study populations. The population of the previous study was involved in an investigation of respiratory disease outbreaks in Ontario, which may suggest why the proportion of horses that were vaccinated prior to the outbreaks was low (Diaz-Mendez et al., 2010). Alternatively, the horses in the current study may be highly vaccinated due to their frequent participation in equestrian events. Although vaccination is not required to participate in most shows in Ontario, it is recommended practice for horses that travel frequently (Wright and Kenney, 2004).

The absence of a statistically significant difference between opportunities for contact at the home facility and while away from home could be due to the small sample size in this study.
Regardless, questionnaire responses indicated that participants reported decreased horse-to-horse contact when travelling away from home. This indicated that the potential for disease transmission while travelling away from home may be reduced due to an owner’s awareness of good biosecurity practices. These results might be an overestimate due to obsequiousness bias, where participants could have responded with what they deemed would be an acceptable answer (i.e., that they vaccinate their horse because it is recommended practice, even if they do not). Steps to minimize this bias were taken by emphasizing the anonymous nature of the questionnaire and through the use of the locked questionnaire submission box.

The majority of horses in the one-mode network were secondary contacts, demonstrating the high amount of connectivity beyond the primary horses that attended the show. Simply planning disease intervention strategies based on the horses that attended the show without explicit consideration of secondary contacts would severely underestimate the resources required to control a potential outbreak. The quantification of contacts at an equestrian show can aid in developing disease management plans in the event of a future inadvertent introduction of an equine disease. In addition, visualizing the contact network associated with an equestrian show can act as an education tool to demonstrate the importance of practicing good biosecurity behaviours.

The low density of the network indicates that the likelihood of an infectious disease spreading to every horse in the network by direct contact is low. However, the impact of this effect is difficult to measure without the consideration of incoming and outgoing infection chains, which can only be measured in directed networks while considering the chronological order of the contacts (Büttner et al., 2013). The high clustering coefficient was likely due to the naturally clustered nature of equine facilities, as horses in the same location had direct
connections with one another, creating multiple clusters of horses. The high clustering coefficient might indicate that a highly infectious disease could potentially spread quickly within a single facility.

The two horses with the highest betweenness and closeness centrality scores had contact with horses in three locations, indicating that they were the most important horses for potential disease spread in the network. In terms of disease transmission, centrality measures can indicate influential nodes in the network; betweenness centrality can indicate gatekeepers for transmission, and closeness centrality indicates a horse that is a short distance from most others, so a disease from a random horse in the network could potentially reach the central horse quickly (Dubé et al., 2009; Martínez-López et al., 2009). The two horses with the highest scores acted as cutpoints between two separate locations at the fairgrounds, allowing horses in these locations to be connected in the network. This type of information could be useful during the design/planning stages of boarding locations at equestrian shows. If these two horses had co-boarded at the same location at the fairgrounds, the network would consist of three separate components, which would lead to a reduced risk of disease since horses from each component would not be reachable from the others.

Nodes with high betweenness centrality values but low Eigenvector values can act as important gatekeepers for disease transmission because they connect otherwise isolated horses to the central core of the network (Dorjee et al., 2013). The horse with these corresponding scores was the only horse from its home facility that participated in the show, which means that potential disease spread to/from the home facility could only occur through that horse. Nodes with low betweenness scores but high Eigenvector values have direct contact to important nodes in the network (Dorjee et al., 2013). The two horses with these corresponding scores were
neighbours to the horses that acted as the central connecting nodes between the coverall barn and the field.

Limitations of this study include the potential for recall bias, as participants completed the questionnaire on-site and did not have access to their horses’ records to answer questions regarding their previous travel patterns and vaccination histories. Some questions were designed to minimize recall bias by providing categories for participants to select an answer (i.e., questions about the number of owners per facility and the average range of horses transported on/off the facility per month). Individuals that travelled with their horse(s) more often might have been less precise in their estimate of the number of times their horse(s) travelled in the 6 months prior to the show date, while those that travelled less often might have been more likely to recall the number of times that they had travelled. Limitations of the network analyses include the static nature of the network, as this does not consider the effect of changing contact structure as horses move in and out of the home facility. It is important to note that the static nature of the network means that the network measures calculated in this study may not persist beyond the study period. In addition, the network structure and characteristics may change if movements beyond this competition were incorporated. Further research should explore the effect of ongoing movements within the equine population on the network structure and potential disease dynamics.

Previous equine contact networks have used a variety of definitions for connections between horses and locations, including connections between racehorse trainers while racing together (Christley and French, 2003) and connections between equine facilities as horses moved between them (Sánchez-Matamoros et al., 2013). Co-attending the same competitions has been used previously in the UK sheep population as a proxy for a connection in network analysis.
(Webb, 2005). In the absence of detailed data on direct contacts within facilities, the definition of a contact in this current study may be an oversimplification because it assumes that all horses in the same location have the same probability of contacting one another. Additionally, the definition of a contact between horses may depend on the specific disease of interest. For example, an assumption that horses are in contact with one another at the same location may be reasonable for respiratory diseases such as equine influenza, which can be transmitted via airborne respiratory droplets (Timoney, 1996). Further investigations are required to determine the frequency and intensity of direct contact between horses co-boarding in the same location.

3.6 Conclusions

To the authors’ knowledge, this study provides the first description of an equine contact network in Ontario, Canada. Questionnaire responses indicated that horses attending the show were vaccinated for diseases such as rabies, equine influenza, and equine herpesvirus, and participants acted preventatively by reducing opportunities for direct and indirect contact while travelling away from home. The contact structure described in this study can be used to determine effective disease prevention and control strategies to reduce the risk of future outbreaks in this population.

3.7 References


Ortiz-Pelaez, A., Pfeiffer, D.U., Soares-Magalhães, R.J., Guitian, F.J., 2006. Use of social network analysis to characterize the pattern of animal movements in the initial phases of the


### Table 3.1. Descriptive home facility characteristics, obtained from questionnaires collected at an equestrian show in Ontario, Canada.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Proportion</th>
<th>Percent (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of owners with horses at facility</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>7/55</td>
<td>12.7</td>
</tr>
<tr>
<td>2 – 3</td>
<td>4/55</td>
<td>7.3</td>
</tr>
<tr>
<td>4+</td>
<td>44/55</td>
<td>80.0</td>
</tr>
<tr>
<td>Types of horses at facility (^a), (^b)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Breeding mares</td>
<td>17/54</td>
<td>31.4</td>
</tr>
<tr>
<td>Foals</td>
<td>15/54</td>
<td>27.8</td>
</tr>
<tr>
<td>Seniors</td>
<td>43/54</td>
<td>79.6</td>
</tr>
<tr>
<td>Number of resident horses transported on/off facility per year</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 – 5</td>
<td>33/55</td>
<td>60.0</td>
</tr>
<tr>
<td>6 – 10</td>
<td>9/55</td>
<td>16.4</td>
</tr>
<tr>
<td>11 – 15</td>
<td>6/55</td>
<td>10.9</td>
</tr>
<tr>
<td>16 – 20</td>
<td>7/55</td>
<td>12.7</td>
</tr>
</tbody>
</table>

\(^a\) The number of participants that indicated that type of horse resided at the facility. Participants could choose more than one category to describe the horses at their home facility.

\(^b\) One participant did not provide a response to this question on the questionnaire.
Table 3.2. Owner-reported horse movements from home facilities, collected at an equestrian show in Ontario, Canada.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Mean</th>
<th>Median</th>
<th>Min.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of boarding horses at home facility</td>
<td>22</td>
<td>12</td>
<td>2</td>
<td>85</td>
</tr>
<tr>
<td>Number of new incoming horses per year</td>
<td>35.1</td>
<td>3.5</td>
<td>0</td>
<td>500</td>
</tr>
<tr>
<td>Off-site trips relative to show date Past 6 months</td>
<td>5.6</td>
<td>3.5</td>
<td>0</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>Next 6 months a</td>
<td>9.2</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Overnights at another facility in past 12 months</td>
<td>11.5</td>
<td>2</td>
<td>0</td>
<td>120</td>
</tr>
</tbody>
</table>

a Based on participants’ estimate of how many trips were planned during this time period.
Table 3.3. Descriptive measures of the one-mode network of horses attending a single equestrian show in Ontario, Canada.

<table>
<thead>
<tr>
<th>Network measure</th>
<th>Number</th>
<th>Median</th>
<th>Min.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nodes</td>
<td>779</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Edges</td>
<td>16032</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>0.05</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diameter</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clustering coefficient</td>
<td>0.97</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average path length</td>
<td>3.28</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Degree</td>
<td></td>
<td>33</td>
<td>1</td>
<td>105</td>
</tr>
<tr>
<td>Betweenness centrality</td>
<td></td>
<td>0</td>
<td>0</td>
<td>65156.18</td>
</tr>
<tr>
<td>Closeness centrality a</td>
<td></td>
<td>0.0042</td>
<td>0.0018</td>
<td>0.0042</td>
</tr>
<tr>
<td>Eigenvector centrality</td>
<td></td>
<td>0.000068</td>
<td>0</td>
<td>0.11</td>
</tr>
</tbody>
</table>

*a Calculated as normalized closeness centrality.*
Figure 3.1. Geographic distance between participants’ home facilities and the equestrian show location.
**Figure 3.2.** Type of horse-to-horse contact occurring at home facility and while travelling.

Percentage of participants that stated there were opportunities for contact between horses at their home facility (dark grey bars) and while travelling away from home (light grey bars). Types of contact included ways in which infectious diseases could potentially be transmitted.
Figure 3.3. Two-mode network of primary and secondary horse contacts. The square nodes represent locations and the circle nodes represent horses. An edge represents a connection between a horse and a location.
Figure 3.4. Horse contacts projected as a one-mode network. All nodes represent horses, and edges represent connections facilitated through being in a common location. Node colours represent betweenness centrality scores. The size of the node represents degree, where larger nodes have a higher degree and smaller nodes have a lower degree.
CHAPTER FOUR

Estimating the potential for disease spread in horses associated with an equestrian show in Ontario, Canada using an agent-based model

Submitted to Preventive Veterinary Medicine, July 2017

4.1 Abstract

Participation in equestrian shows provides opportunities for contact between horses, increasing the risk of disease introduction and spread in the population. An understanding of equine contact patterns can assist in estimating the potential magnitude of an outbreak in order to inform effective disease prevention and control strategies. The objectives of this study were to 1) examine the potential spread of equine influenza in a network of horses associated with a 2-day equestrian show in Ontario, Canada; and 2) evaluate several interventions to determine their effectiveness in minimizing the extent of a simulated outbreak. A discrete-time, stochastic, agent-based simulation model was constructed to represent horses and facilities associated with the show, including both horses that attended the show, and horses that were not in attendance but co-boarded with attending horses at their home facilities. At the beginning of each simulation run, one random horse in attendance at the show was infected with equine influenza. Model outcomes, including the attack rate, average outbreak duration, and effective reproductive number, were evaluated over a 90-day period. Quarantine of horses attending the show for 14 days upon return to their home facility was the most effective intervention, resulting in a 93% reduction in the average attack rate. In instances where quarantine for 14 days would not be feasible, quarantine for shorter time periods was effective when combined with targeted increases in initial facility-level vaccine coverage. This study demonstrates a relative comparison
of intervention effectiveness for reducing the projected attack rate of an equine influenza outbreak in a population of horses associated with a single equestrian show. The results have the potential to inform and improve the current strategies used to prevent the introduction and spread of equine diseases, while minimizing the economic and health impacts of disease within the equine industry.

4.2 Introduction

The nature of equestrian sport and competition events brings horses from different boarding facilities into contact with each other. The mixing of horses at facilities which are unique to them provides opportunities for the potential introduction and spread of infectious diseases. There are several examples of large disease outbreaks that have been associated with horses attending equestrian shows (Morley et al., 2000; Satou and Nishiura, 2006; Traub-Dargatz et al., 2013). In 2007, equine influenza was diagnosed in a horse at a boarding centre in Australia, and the pathogen was subsequently spread throughout the country as horses travelled to attend equestrian shows and events (Moloney, 2011; Wong, 2011). In 2011, an outbreak of equine herpesvirus occurred after horses attended a national event, resulting in subsequent spread in the USA and Western Canada (Traub-Dargatz et al., 2013). In 2016, an outbreak of equine influenza occurred in Atlantic Canada after horses attended various equestrian events during the fall fair season (MacPhee, 2016). While these examples provide insight into outbreaks linked to equestrian shows and events, the literature reports are biased towards outbreaks that have spread widely or which exhibited significant morbidity and/or mortality. Therefore, it is likely that there are also occurrences of smaller outbreaks that are not captured in the peer-reviewed literature, but might be of importance to horse owners or event organizers as they highlight the need for
increased awareness of the risk of disease spread.

Retrospective analyses of outbreaks are beneficial to understand risk factors associated with disease spread for the development of disease control strategies (Firestone et al., 2011; Traub-Dargatz et al., 2013) and to improve outbreak preparedness (Garner et al., 2011b; Lewis et al., 2015). However, developing a more refined understanding of potential disease spread prior to an outbreak can lend support to disease management plans both before and after an equine event. Simulation models are tools that can incorporate known disease dynamics and underlying contact patterns to describe a potential outbreak in a population (McNab et al., 2011). Models can also be used to evaluate the effectiveness of disease interventions which may not be practical to test in the population of interest (Mishra et al., 2011). Models have been previously used in equine populations to understand disease dynamics (Glass et al., 2002; Satou and Nishiura, 2006; Daly et al., 2013), to characterize transmission of viral equine pathogens (Park et al., 2009; Hughes et al., 2012), and to evaluate equine disease control strategies (de la Rua-Domenech et al., 2000; Park et al., 2003; Baguelin et al., 2010; Garner et al., 2011a; Perkins et al., 2011; Rosanowski et al., 2016).

The objectives of this study were to examine the potential for disease spread in a network of horses associated with a 2-day equestrian show in Ontario, Canada, and to evaluate interventions to determine their effectiveness in minimizing the extent of a simulated outbreak. For the purpose of this study, we used equine influenza as an exemplar pathogen. Equine influenza is a respiratory disease caused by a highly contagious influenza A virus (Timoney, 1996). Equine influenza can be transmitted between horses through direct contact with respiratory droplets, and indirect transmission can occur through contact with fomites such as contaminated equipment (Landolt, 2014). Additionally, the natural history of equine influenza
has been well-characterized through various challenge studies (Mumford et al., 1988; Newton et al., 2000; Park et al., 2004) and field observations (Cullinane et al., 2001; Newton et al., 2006; Gildea et al., 2013), making it an ideal candidate to use in our simulated host-pathogen system.

4.3 Materials and methods

4.3.1 Study population

The study population consisted of horses associated with a two-day provincial-level sanctioned dressage show in southwestern Ontario, Canada in 2014 (Equestrian Canada, 2016). Data collection and descriptive characteristics of the study population have been previously described (Spence et al., 2017). To summarize, information on horse age, sex, vaccination status, and home facilities were collected from horse owners at the show using a questionnaire. There were 69 horses attending the show (referred to as “attending horses”), and questionnaire responses were received for 55 of the 69 horses (79.7% questionnaire response rate, Spence et al., 2017). In the current study, horses that attended the show but whose owners did not complete the questionnaire (14/69 horses) were excluded from the population due to the absence of information on their potential contacts. From the questionnaire responses, an additional 710 horses (referred to as “non-attending horses”) were identified as residing at the 38 home facilities of the attending horses (Spence et al., 2017). The model was developed to replicate the observed contact network of the 765 horses (55 attending horses and 710 non-attending horses, Spence et al., 2017).
4.3.2 Model description

A discrete-time, stochastic, agent-based simulation model was constructed using AnyLogic 7.3.6 (XJ Technologies, St. Petersburg, Russia). Agent-based models allow for the description of autonomous “agents” in a population, which can include individual animals or locations. Agent-based models have been previously used to explore within-herd disease dynamics (Jiang et al., 2012; Robins et al., 2015), evaluate disease surveillance and control strategies (Lewis et al., 2015; Arruda et al., 2016, 2017), and describe interactions between animals, humans, and the environment (Chen et al., 2013; Havas et al., 2014). In this current study, an agent-based model was selected because it could describe a high degree of individual-level heterogeneity in the population, including variability in susceptibility, infectiousness, and contact patterns (Lanzas and Chen, 2015).

The model described two types of agents: horses and locations. Horses were individual-level agents described by associated state variables, including their identification number, vaccination status, and disease status. Locations were represented as aggregating “collective agents”, which defined the connections between individual horses within a location at a given time. Locations included 38 home facilities (which housed both attending horses and non-attending horses) and 3 boarding locations at the competition venue (which housed only attending horses). The competition venue was comprised of three distinct areas where attending horses could be located: stabling barn #1 (SB1), stabling barn #2 (SB2), and the daily ship-ins (SI), located in a field at the venue.
4.3.3 **Process overview**

One time step represented one day, and the model was run for 90 days. During each time step \((t)\), horses executed a specific sequence of discrete-event processes that defined their individual contacts based on their associated location (Figure 4.1). At the beginning of the simulation \((t = 0)\), horses were located in their respective home facilities. One day later \((t = 1)\), the attending horses travelled to the competition venue and were assigned to their boarding location, and therefore had a different group of horse contacts. There were 15 horses boarded in SB1, 20 horses boarded in SB2, and 15 horses in SI (Spence et al., 2017). Attending horses returned to their home facilities after two days \((t = 3)\). This movement pattern describes a dynamic network where contact between horses occurs when they are present in the same location and contact ends once they are no longer in the same location. We assumed that all horses remained in their respective location (SB1, SB2, SI) at the competition venue for the entire duration of the show, and that all horses boarded at the individual home facilities remained in their location for the duration of the model simulation. The input data used to assign horses to their respective locations are provided as supplementary materials (Appendix III).

4.3.4 **Equine influenza infection**

At the beginning of the simulation, one horse that was attending the show was randomly “infected” with a disease that exhibited the same natural history characteristics as equine influenza (Figure 4.2). An attending horse was the index case in all simulation runs, as we assumed that this scenario represented the highest risk for continued spread within the larger population. The process of disease initialization (i.e., the infection of a randomly chosen attending horse) in each simulation run was stochastic.
The equine influenza disease process followed a susceptible-exposed-infectious-recovered (SEIR) design, while considering the differences in the natural history of the disease between unvaccinated and vaccinated horses (Figure 4.2). Susceptible horses were assumed to have no immunity to equine influenza either as a result of vaccination or natural infection. We assumed that homogeneous mixing occurred within a location, so that all horses in the same location had an equal probability of contacting one another. Equine influenza transmission was a stochastic process, where infected horses could directly transmit equine influenza at a defined effective contact rate, conditional on the probability of transmission per effective contact (Table 4.1). The differing probability of transmission between unvaccinated and vaccinated horses accounts for the reduced infectiousness of vaccinated horses (Park et al., 2003). We did not consider indirect transmission (e.g., via contaminated fomites) because we were only interested in the possibility of direct transmission via the horse contact network. Furthermore, we assumed that direct transmission of equine influenza was most important, given the respiratory nature of the disease (Timoney, 1996).

The latent and infectious periods were defined according to the published literature (Park et al., 2003). Infectious horses could transmit equine influenza to horses in both the susceptible and vaccinated compartments for the duration of the infectious period, but the probability of a vaccinated horse transmitting equine influenza was half that of an unvaccinated horse (Table 4.1). Vaccination against equine influenza does not provide complete immunity to infection in all horses, but instead reduces the appearance of clinical signs, the probability of transmission, and the duration of the infectious period (Mumford et al., 1994; Park et al., 2003; Kannegieter et al., 2011) (Table 4.1). Due to the variability in published estimates regarding the level of acquired immunity from equine influenza vaccination, we assumed that vaccine effectiveness was 50%
(Table 4.1). This meant that there was a 50% probability that a vaccinated horse would become infected upon effective contact with an infectious horse. If the vaccinated horse did not become infected upon effective contact (i.e., the vaccine conferred protection), the horse remained in the vaccinated compartment, but could potentially be infected by a different horse at a later time.

4.3.5 Equine influenza vaccination

Attending horses with a known equine influenza vaccination status (as previously described by Spence et al. (2017)) were assigned to the vaccinated compartment prior to model start. Since the vaccination status was only known for attending horses, we made assumptions about the initial proportion of vaccinated non-attending horses. We assumed that the initial proportion of horses vaccinated in each home facility (referred to as the initial facility-level vaccine coverage) was a minimum of 36%, informed by an outbreak investigation in Ontario, Canada (Diaz-Mendez et al., 2010). Non-attending horses were randomly assigned to the vaccinated compartment until at least 36% of horses in that home facility were vaccinated (Appendix III). The assignment of non-attending horses to the vaccinated compartment was stochastic, as the individual horses that were assigned to the vaccinated class could vary between simulation runs. In smaller home facilities, the initial facility-level vaccine coverage could exceed 36% because the number of horses required for vaccination was less than one. For example, if there were only two horses boarded at a home facility, the vaccination of one horse would bring the initial facility-level vaccine coverage to 50%. All vaccination was considered to have occurred before the start of the simulation, and revaccination during the simulation was not considered.
4.3.6 Model outcomes

The outcomes of interest included: the attack rate, defined as the proportion of infected horses in the total population, the average outbreak duration (in days), and the effective reproductive number (Re), defined as the average number of secondary infections generated from each infectious case, given that a proportion of the population is vaccinated (Mishra et al., 2011). Due to model stochasticity, each model scenario was run for 1000 iterations. The base case scenario described the magnitude of the simulated outbreak in the absence of control measures other than pre-existing vaccine coverage, and was used as a comparison to determine intervention effectiveness. The percent change in the attack rate between the base case and intervention scenarios was calculated using the average value in each simulation run. Data were summarized using Stata (StataCorp. 2013. Stata Statistical Software: Release 14. College Station, TX: StataCorp LP) and the ‘ggplot2’ package in R (Wickham, 2009).

4.3.7 Interventions

The model was used to test three intervention strategies: 1) quarantine of attending horses upon return to their home facility; 2) targeted increases in the initial facility-level vaccine coverage (prior to horse show season); and 3) a combination of quarantine and increased initial facility-level vaccine coverage. For the first intervention strategy, all attending horses were quarantined (i.e., could not contact any other horse) once they returned to their home facility for 2 days, 5 days, or 14 days. These time periods were chosen to determine the length of time that could be recommended for quarantine to control transmission of equine influenza in a facility (Canadian Food Inspection Agency, 2016). In addition, a range of time periods were selected due to the potential for non-compliance, as horse owners might not be able or willing to quarantine
their horse for a long period of time.

For the second intervention strategy, home facilities received targeted increases in initial vaccine coverage dependent on two facility-level risk factors captured by questionnaire responses in Spence et al. (2017). The first risk factor was the number of individual owners with horses boarded at each home facility, assuming that facilities with many different owners are higher-risk facilities for disease introduction. The second risk factor was the average number of boarded horses (both attending and non-attending) that moved on and off the facility per month, assuming that facilities with high rates of turn-over are higher-risk facilities for disease introduction. Home facilities were divided into categories based on their characteristics for each risk factor (Table 4.2). For the targeted vaccination intervention, independent model simulations were run where the initial facility-level vaccine coverage in the home facilities within the category was increased from 36% to 50% and 75%. We assumed that a facility-level vaccine coverage of 100% would be difficult to achieve in reality, and thus the maximum level of vaccine coverage tested in the intervention scenarios was 75%.

4.3.8 Model validation and sensitivity analysis

Model validation was conducted to ensure that the base case outcomes of interest were comparable to those reported in the peer-reviewed literature. The base case scenario was run for 1000 iterations and the average outbreak duration and average Re were compared to previous estimates in the peer-reviewed literature (Morley et al., 2000; Satou and Nishiura, 2006; Nishiura and Satou, 2010).

Univariate sensitivity analyses were conducted to assess the impact of assumptions regarding certain model parameters on the main outcome of interest. Sensitivity ($\Sigma$) is defined as
the proportional change in the outcome \( V \) (e.g. attack rate) for a given change in a parameter value \( P \) from its default value in the base case scenario \( P_0 \) (Keeling and Gilligan, 2000; Webb et al., 2006):

\[
\sum \approx \ln \left[ V(P) \right] - \ln \left[ V(P_0) \right] / \ln (P) - \ln (P_0).
\]

Sensitivity measures the importance of the input parameter relative to the outcome, where large sensitivity values (\( \sum > 1 \)) indicate that the model is sensitive to the changes in parameter value(s) (Keeling and Gilligan, 2000; Webb et al., 2006). To determine the sensitivity of parameter values with a high degree of potential uncertainty, we independently varied the initial facility-level vaccine coverage, the contact rate, and vaccine effectiveness. To assess the appropriateness regarding our assumption of a “blanket vaccine coverage”, we increased the initial facility-level vaccine coverage in large facilities (defined as facilities that housed \( \geq 20 \) horses) from 36% to 50% and 75% to observe any changes in the attack rate. While the transmission rate of equine influenza (a combination of the contact rate and the probability of transmission per effective contact) has been previously estimated (Glass et al., 2002), there is little information on the within-facility contact rate for horses. Therefore, for our sensitivity analysis, we chose a biologically plausible range defined as a minimum contact rate of 1 horse per day and a maximum contact rate of 6 horses per day, varied in increments of 1. Lastly, given the uncertainty and high level of variability surrounding the degree of individual immunity provided by equine influenza vaccination (Paillot, 2014), we varied the parameter for vaccine effectiveness between 25% and 75% (from the base case value of 50%).
4.4 Results

4.4.1 Model validation and base case results

In the base case scenario, the average attack rate was 4.24% (SD = 3.80%, range = 0.13 – 20.78%) and the average outbreak duration was 19.6 days (SD = 4.3 days; range = 7 – 39 days). The average outbreak duration was comparable to previously reported ranges of equine influenza outbreak durations (18 – 30 days in a partially vaccinated population of horses in Saskatchewan, Canada (Morley et al., 2000) and 14 – 20 days in a partially vaccinated population of horses in Japan (Nishiura and Satou, 2010)). The average Re was 2.4 (SD = 0.6, range = 1.0 – 7.0), which was within the range of previously reported Re values for equine influenza in a partially vaccinated equine population (estimates of 2 – 5 (Satou and Nishiura, 2006), and 2.4 – 24.7 (Nishiura and Satou, 2010)).

4.4.2 Interventions

Quarantine of attending horses upon return to their home facilities resulted in an overall decrease in the average attack rate and average outbreak duration (Figure 4.3). Quarantine for 5 days resulted in a 90% reduction in the average attack rate (mean = 0.43%, SD = 0.65%, range = 0.13 - 4.97%). Quarantine for 14 days resulted in a 93% reduction in the average attack rate, which was the lowest average attack rate compared to the other intervention scenarios (mean = 0.29%, SD = 0.13%, range = 0.13 – 0.78%). In addition, the average outbreak duration decreased as quarantine time increased, with quarantine for 5 days resulting in an average outbreak duration of 8.90 days (SD = 4.40 days, range = 7 – 34 days) and quarantine for 14 days resulting in an average outbreak duration of 7.75 days (SD = 0.72 days, range = 7 – 10 days). Both quarantine for 5 days and 14 days resulted in the same average Re of 1.5 (SD = 0.7, range = 1.0 –
The vaccination strategy that resulted in the lowest average attack rate was targeting facilities with four or more owners and increasing their initial facility-level vaccine coverage to 75% (Figure 4.3). This strategy resulted in a 29% decrease in the average attack rate (mean = 3.02%, SD = 2.99%, range = 0.13 – 22.48%), but an increase in the average outbreak duration (mean = 20.95 days, SD = 7.53, range = 7 – 59 days). This strategy also resulted in the same average Re as the base case scenario (mean = 2.5, SD = 0.69, range = 1.0 – 8.0). Targeting facilities for increased vaccine coverage based on the average number of horses moved on/off the home facility per month (with facilities with high turnover receiving the targeted vaccine intervention) was not as effective as the other interventions in decreasing the average attack rate (Figure 4.3). Increasing the initial facility-level vaccine coverage to 75% in facilities with one to five horses moving on/off the facility per month resulted in the lowest average attack rate for this risk factor (mean = 3.79%, SD = 3.89%, range = 0.13 – 24.97%), which was an 11% decrease from the base case scenario. For all categories of this risk factor, the average outbreak duration was similar to the observed outbreak duration in the base case scenario without the intervention (average value ranged from 19.37 days – 20.30 days).

When quarantine and the targeted increase in initial facility-level vaccine coverage were combined, any combination that included quarantine of attending horses for 14 days upon return to their home facilities was the most effective at decreasing the attack rate (Figure 4.3). However, these combinations resulted in a 93% reduction in average attack rate, which was the same percent change from the base case scenario as the quarantine intervention alone. Quarantine for 5 days in combination with 75% vaccine coverage for facilities with four or more owners resulted in a 93% decrease in the average attack rate (mean = 0.31%, SD = 0.24%, range
= 0.13 - 3.53%) and an average outbreak duration of 8.09 days (SD = 2.61 days, range = 7 – 34 days) (Figure 4.3). This scenario also resulted in a decreased average Re of 1.4 (SD = 0.8, range = 1.0 – 7.0). The additional increase in vaccine coverage resulted in an average attack rate that was 28% less than quarantine alone and 90% less than increased vaccine coverage alone.

While quarantine for 2 days was not an effective intervention by itself, it resulted in a decreased attack rate when combined with vaccination (Figure 4.3). The greatest reduction in the attack rate occurred when horses were quarantined for 2 days and the initial facility-level vaccine coverage was increased to 75% in facilities with four or more owners. This intervention scenario resulted in an average attack rate of 2.20% (SD = 2.67%, range = 0.13 - 16.99%), which was 48% less than the base case scenario, 44% less than quarantine alone and 27% less than vaccination alone. This scenario also resulted in a similar average outbreak duration (mean = 19.75 days, SD = 8.79 days, range = 7 – 57 days) and a similar average Re (mean = 2.1, SD = 0.7, range = 1.0 – 7.0) to the base case scenario.

4.4.3 Sensitivity analysis

The model-projected attack rate appeared to be insensitive to variations in parameters for the contact rate, initial facility-level vaccine coverage, and vaccine effectiveness ($\Sigma < 1$) (Table 4.3). The greatest variation in the attack rate occurred when the parameter for the contact rate was increased. When the contact rate was increased to 6 horses per day, the average attack rate increased to 7.14% (SD = 5.58%, range = 0.26 - 35.95%), a 68% increase from the base case value.
4.5 Discussion

The results of this study support the recommendation that horses should be quarantined for a period of time sufficient to rule out infection after returning home from another location (Canadian Food Inspection Agency, 2016). There is little published data to indicate the general quarantine time period that could be used when horses return to their home facility after being off property (Weese, 2014). Previous research has indicated that a 21-day isolation period could be used to ensure freedom from equine influenza in a facility following an outbreak (Morresey, 2016). However, the benefits of using quarantine protocols as a preventive measure before an outbreak is identified have not been extensively demonstrated.

While quarantine for 14 days resulted in a greater decrease in the average attack rate compared to quarantine for 5 days (93% vs. 90% reduction), the difference in implementing a 14-day quarantine period compared to a 5-day quarantine period is substantial from a management perspective. Rosanowski et al. (2012) demonstrated that the day-to-day usage of general biosecurity measures on horse facilities in New Zealand was poor, and would thus be insufficient to prevent disease introduction into these facilities. As such, the recommendation of a 5-day quarantine period (as compared to a 14-day quarantine period) would potentially receive greater acceptance for implementation by horse owners. A 14-day quarantine period would be most beneficial for facilities with any level of vaccine coverage, or when the vaccination status of individual horses within the facility is unknown. At a higher level of vaccine coverage, 2- or 5-day quarantine periods could be used to decrease the average attack rate in situations where quarantine for 14 days would not be feasible.

Increasing facility-level vaccine coverage demonstrated that in this population of horses, targeting facilities based on the number of horse owners was more effective than targeting
facilities based on the number of boarded horses that were moved on/off the facility per month. This finding might be explained by examining the proportion of home facilities within each risk factor category. For example, 78.9% of home facilities had four or more owners boarding horses at their facility, compared to only 10.5% of home facilities that had a large number of horses (16 – 20) moving on/off the facility per month. Additional analysis demonstrated that similar results were achieved when a large proportion of facilities (75%) were randomly targeted for increased vaccine coverage (Appendix III). It is also of note that approximately 94% of higher-frequency movements (i.e., >5 movements) occurred in facilities with four or more owners (Appendix III). Thus, it is possible that a combination of the large proportion of the population targeted by the strategy of four or more owners, and the fact that high-risk movements were captured by it, contributed to its success. Further analysis is required to explore the effects of targeting facilities based on these potential risk factors, and to determine whether it is more effective to target facilities based on these risk factors compared to randomly targeting a large proportion of facilities in the population.

Previous models used to investigate equine influenza outbreaks have included stochastic, differential equation models (Glass et al., 2002; Park et al., 2003; Baguelin et al., 2010), which have limitations regarding the inclusion of horse characteristics and detailed contact patterns. Stochastic, state-transition simulation models have also been used to evaluate disease control strategies between facilities, while incorporating spatial and temporal elements (Garner et al., 2011a; Rosanowski et al., 2016). The advantage of using an agent-based model, such as the one used in this study, includes the ability to describe the evolving individual-level interactions between horses within facilities as they come into contact with each other through attending a show. In addition, the description of horses as individual agents in the model allows for targeted
interventions at the horse-level instead of the premises-level. This is important for the recommendation and implementation of disease control strategies in horse facilities, as the management practices for individual horses within facilities can vary depending on their owner (Morresey, 2016).

A similar approach of collecting equine travel data and incorporating the network into an individual-based model is described by Hayama et al. (2012). Hayama et al. (2012) provided insight into surveillance strategies for equine infectious anemia while considering the risk of travel within and between various equine sectors. The description of equine contact and movement networks for use in estimating risk of disease spread has become more common in equine populations, with current research highlighting the importance of understanding these contact patterns (Christley and French, 2003; Firestone et al., 2011; Sánchez-Matamoros et al., 2013). The inclusion of empirical equine network data in computer simulation models provides the ability to support evidence-based recommendations for disease prevention and control strategies.

The effect of targeted increases in vaccination and use of quarantine prior to a confirmed outbreak have not been extensively reported in the literature. Nishiura and Satou (2010) used a modeling approach to determine the effects of combined disease prevention and control measures during an outbreak, including vaccination, movement restrictions, isolation, and quarantine. The authors found that these disease prevention and control measures greatly reduced the number of secondary transmissions; however, the relative contribution of each measure could not be determined (Nishiura and Satou, 2010). Previous models have demonstrated the effectiveness of reactive vaccination (i.e., vaccination in the face of an outbreak), especially when implemented early (Baguelin et al., 2010; Garner et al., 2011a; Rosanowski et al., 2016).
However, demonstrating the benefits of increased vaccine coverage prior to an outbreak can highlight the importance of using such prevention strategies to ensure preparedness in the event of an outbreak.

There are some limitations inherent with this type of modeling that are worthy of discussion. First, the conclusions drawn from this model are dependent on the demographic data and contact structure described by Spence et al. (2017). The exclusion of horses whose owners did not complete the questionnaire (i.e., non-responders) underestimates the size of the population associated with the show, and therefore underestimates the magnitude of the projected outbreak. In addition, the network structure described in the model does not consider any horse contacts beyond the study population (e.g., any future shows that the horses might have attended). As such, the projected attack rates should be interpreted as conservative estimates. We also assumed that the contact rate was the same at both the competition venue and at individual home facilities, which is likely an oversimplification. In order to appropriately parameterize the contact rate, empirical data are needed to provide a more detailed understanding of the opportunities for contact within various equine facilities. For example, this study did not consider any interactions that horses may have had if they were located in common areas of the competition venue (e.g., warm-up area). Despite these simplifications, this research provides an improved understanding of the opportunities for disease spread in a population of horses associated with an equestrian show.

Opportunities for future research include describing indirect transmission pathways of equine influenza, as only direct transmission was considered in the current study. This would allow for the incorporation of biosecurity and infection control practices directed towards preventing indirect spread, such as hand-washing and changing clothes and shoes, into models.
(Firestone et al., 2013). The ability and willingness of facilities to implement quarantine protocols and increased vaccination should also be studied; for example, it is possible that not all facilities are equipped with the infrastructure to implement the necessary quarantine measures (Arthur and Suann, 2011; Canadian Food Inspection Agency, 2016). Lastly, this model could be used as a knowledge translation tool to communicate the potential risks of attending an equestrian show, as well as the potential interventions that could be used to reduce the risk of disease spread upon return to the home facility.

4.6 Conclusions

This study has provided an overview of disease prevention and control strategies that could reduce the projected attack rate of an equine influenza outbreak in a population of horses associated with a single equestrian show. Quarantine of attending horses upon return to their home facility for 14 days was the most effective intervention, resulting in a 93% reduction in average attack rate. In instances where quarantine for 14 days would not be feasible, quarantine for shorter time periods (2 or 5 days) could be effective in minimizing outbreak size in combination with targeted increases in initial facility-level vaccine coverage. These results can be used to inform the use of effective disease prevention and control strategies for the potential introduction and spread of disease in equine populations.

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### Table 4.1. Equine influenza disease parameters used in the agent-based model of horses associated with an equestrian show in Ontario, Canada.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Unvaccinated horses</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contact rate</td>
<td>2 horses per day</td>
<td>Assumption</td>
</tr>
<tr>
<td>Probability of transmission</td>
<td>100%</td>
<td>Informed by Park et al. 2003</td>
</tr>
<tr>
<td>Latent period</td>
<td>1.75 days</td>
<td>Park et al. 2003</td>
</tr>
<tr>
<td>Infectious period</td>
<td>4.8 days</td>
<td>Park et al. 2003</td>
</tr>
<tr>
<td><strong>Vaccinated horses</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Degree of vaccine protection</td>
<td>50%</td>
<td>Assumption</td>
</tr>
<tr>
<td>Contact rate</td>
<td>2 horses per day</td>
<td>Assumption</td>
</tr>
<tr>
<td>Probability of transmission</td>
<td>47%</td>
<td>Informed by Park et al. 2003</td>
</tr>
<tr>
<td>Latent period</td>
<td>2.52 days</td>
<td>Park et al. 2003</td>
</tr>
<tr>
<td>Infectious period</td>
<td>2.48 days</td>
<td>Park et al. 2003</td>
</tr>
</tbody>
</table>
Table 4.2. Description of categories for targeted increases in initial facility-level vaccine coverage in the agent-based model.

<table>
<thead>
<tr>
<th>Risk factor</th>
<th>Category</th>
<th>Proportion of home facilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of horse owners per facility</td>
<td>Only 1 owner</td>
<td>4/38 (10.5%)</td>
</tr>
<tr>
<td></td>
<td>2 to 3 owners</td>
<td>4/38 (10.5%)</td>
</tr>
<tr>
<td></td>
<td>4 or more owners</td>
<td>30/38 (78.9%)</td>
</tr>
<tr>
<td>Average number of horses moved on or off the home facility per month</td>
<td>1 to 5 horses</td>
<td>25/38 (65.8%)</td>
</tr>
<tr>
<td></td>
<td>6 to 10 horses</td>
<td>4/38 (10.5%)</td>
</tr>
<tr>
<td></td>
<td>11 to 15 horses</td>
<td>5/38 (13.2%)</td>
</tr>
<tr>
<td></td>
<td>16 to 20 horses</td>
<td>4/38 (10.5%)</td>
</tr>
</tbody>
</table>
Table 4.3. Results of the sensitivity analysis of assumed parameter values used in the agent-based model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Mean % (SD)</th>
<th>Range %</th>
<th>Sensitivity (Σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact rate (horses/day)</td>
<td>1</td>
<td>3.01 (3.08)</td>
<td>0.13 – 23.66</td>
<td>0.496</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Base case value</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>4.78 (4.15)</td>
<td>0.26 – 21.84</td>
<td>0.294</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>6.07 (5.01)</td>
<td>0.26 – 27.19</td>
<td>0.516</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>6.59 (5.08)</td>
<td>0.26 – 34.77</td>
<td>0.481</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>7.14 (5.58)</td>
<td>0.26 – 35.95</td>
<td>0.474</td>
</tr>
<tr>
<td>Initial vaccine coverage (%)</td>
<td>36</td>
<td>Base case value</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>4.35 (3.96)</td>
<td>0.13 – 23.40</td>
<td>0.075</td>
</tr>
<tr>
<td></td>
<td>75</td>
<td>4.42 (3.90)</td>
<td>0.26 – 22.75</td>
<td>0.055</td>
</tr>
<tr>
<td>Vaccine effectiveness (%)</td>
<td>25</td>
<td>4.96 (4.43)</td>
<td>0.13 – 28.10</td>
<td>-0.226</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>Base case value</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>75</td>
<td>3.62 (3.39)</td>
<td>0.13 – 21.96</td>
<td>-0.393</td>
</tr>
</tbody>
</table>
Figure 4.1. Schematic of the model process to define contact between horses within locations associated with an equestrian show in Ontario, Canada.
Figure 4.2. Disease states of the equine influenza infection process in the agent-based model.
**Figure 4.3.** Boxplots of the projected equine influenza attack rates in the intervention scenarios.

The top left graph represents the results of the base case scenario in the absence of any interventions. The last three graphs of the left column represent the results of the quarantine scenario alone. The top middle and right graphs represent the results of the targeted vaccination scenarios alone. The bottom and top of each box represent the 25th and 75th percentiles, respectively, and the horizontal line within the box represents the median. Each box represents 1000 simulation runs.
CHAPTER FIVE

A longitudinal study describing horse demographics and movements during a competition season in Ontario, Canada

Submitted to The Canadian Veterinary Journal, August 2017

5.1 Abstract

The objectives of this study were to describe the demographics of horses enrolled in a longitudinal study in Ontario, Canada, and to characterize their movements over a 7-month period. Two hundred and twenty-two owners completed an initial questionnaire to provide demographic information for 570 horses. These horses were enrolled in a longitudinal study to document their movements from May to November 2015 using a monthly questionnaire. The average age of the participating horses was 12.2 years (SD = 6.4 years). The primary discipline of participating horses included competitive disciplines (63.3%), leisure (33.3%), and racing (3.2%). During the 7-month period, there were 3001 unidirectional movements of horses between facilities. Reasons for travel on/off a facility included attending a competition (38.7%), leisure activities (18.8%), and attending performance/training clinics (7.5%). The horse demographic and movement data in this study provide an improved understanding of the characteristics and structure of the Ontario horse population.

5.2 Introduction

The effective prevention and control of equine disease outbreaks depends on the accurate knowledge of the equine population at risk. Descriptions of baseline horse characteristics, such as vaccination histories, horse movement patterns, and the use of biosecurity and infection
control measures by horse owners, can lend support when planning disease prevention, surveillance, and control strategies (Boden et al., 2012, 2013; Rosanowski et al., 2012; Wylie et al., 2013). Horse populations consist of a highly diverse group of horses, ranging from those that compete in sporting/competition events to those that are kept as companion animals. When horses visit locations outside of their home facility, there is a risk of exposure to infectious agents and possibly subsequent spread of infection (Firestone et al., 2011; Rosanowski et al., 2013a; Sánchez-Matamoros et al., 2013). A refined understanding of horse demographics, and the extent of horse movements between facilities, would enable more thorough investigations into the potential for disease spread in the population.

In some countries, details regarding horse demographics and movement patterns can be extracted from existing information sources (Christley and French, 2003; Bell and Drury-Klein, 2011; Sánchez-Matamoros et al., 2013). When existing data are not available, interview and questionnaire-based methods have been used as alternative strategies to describe horse populations in Japan (Hayama et al., 2010), Great Britain (Boden et al., 2013), New Zealand (Rosanowski et al., 2013b), and South Africa (Liebenberg et al., 2016). In Ontario, Canada, there is limited information available surrounding the descriptive characteristics of the horse population. Every five years, the Census of Agriculture, conducted by the Canadian government, provides updated information on the number of horses and their geographical distribution throughout the country (Statistics Canada, 2016). The results of the 2016 Census of Agriculture estimated that there were 64,536 horses and ponies residing on 9,294 farms in Ontario (Statistics Canada, 2016). While this information provides a general overview of horses in Ontario, the demographics and structure of the Ontario horse population has not been previously described in the literature. Having access to comprehensive information on horses and horse facilities in
Ontario is important to inform evidence-based decisions regarding the utility of different disease prevention and control strategies.

The objectives of this study were to 1) describe the characteristics of horses and equine facilities in Ontario, Canada, and 2) collect information on horse movement patterns over a 7-month period (May to November, 2015). The results of this study can inform the creation of a movement network to examine the characteristics of highly connected horses and facilities within the participating population of horses.

5.3 Materials and methods

5.3.1 Study design

This was a descriptive study consisting of two phases: an initial cross-sectional questionnaire (“Enrollment”, March to June, 2015), and a longitudinal study (“Monthly questionnaire”, May to November, 2015). The cross-sectional questionnaire was used to describe the characteristics of participating horses, and to enroll horse owners who completed the questionnaire into the longitudinal study. The longitudinal study was used to collect information on horse movements from the participating owners on a monthly basis. This study was reviewed and approved by the University of Guelph Research Ethics Board (REB#15FE013).

5.3.2 Recruitment

Participant recruitment occurred between March 13th and June 8th, 2015. Due to the absence of an available registry of horses, owners, or facilities in Ontario, a sampling frame could not be established for recruitment and/or sample size calculation. A variety of electronic, print, and in-person methods were used for participant recruitment, including social media.
advertisements and distribution through the mailing lists of relevant equestrian organizations and industry groups. Individuals were eligible to participate in the study if they were 18 years of age or older, resided in Ontario, and were the person responsible for at least one horse. Individuals were invited to participate in the study regardless of the use of their horse and the owner’s estimate of the frequency of travel (i.e., a participant was not required to travel often with their horse to join the study). Individuals were required to have either an email address or a telephone number to participate. Upon enrollment, participants were entered into a draw to win one of three gift cards from an equine equipment store, and received additional entries for each month that they responded during the longitudinal study.

5.3.3 Questionnaire design and data collection

Participants were asked to complete an initial questionnaire upon enrollment into the study. The questionnaire was a modified electronic version of a questionnaire previously tested in a pilot study by Spence et al. (2017). The questionnaire was administered using the survey software Qualtrics (Qualtrics, Provo, Utah, USA) and was beta-tested by a group of researchers, veterinarians, and horse owners. The enrollment questionnaire consisted of 14 open and closed questions regarding the descriptive characteristics of the participant’s horse and the facility where their horse was boarded (referred to as the horse’s “home facility”). Participants could enroll more than one horse (up to 10 horses) if they were the person responsible for all of the enrolled horses. Descriptive horse characteristics that were collected using the questionnaire included age, sex, primary sport/competition discipline (further categorized into racing, leisure, or competitive disciplines for statistical testing), and vaccines administered in the past 12 months. Furthermore, descriptive characteristics of home facilities included the first three digits
of the postal code, the number of other owners that also boarded horses at the facility, the total number of horses at the facility, the primary sport/competition discipline of the horses, and the presence of foals, mares used for breeding purposes, and/or senior horses (16 years or older) at the facility. Each owner was assumed to have their horses boarded at a unique home facility, unless otherwise indicated in their response (i.e., one owner response per home facility). A copy of the enrollment questionnaire is included in Appendix IV.

Participants that completed the enrollment questionnaire provided informed consent to join the longitudinal study, which was a monthly online questionnaire administered using Qualtrics. Questionnaire invitations were sent via email on the afternoon of the last day of the month and included questions about the participating horses’ movements during that month; for example, the first questionnaire was distributed on the afternoon of May 31st and included questions about horse movements during the month of May. Each questionnaire invitation was unique to the participant, so that the response of each participant could be identified.

Each monthly questionnaire followed the same design (an example is included in Appendix IV). At the beginning of the questionnaire, the participant was asked if their horse(s) left the home facility for any duration of time within the month. If the participant responded “no”, their monthly questionnaire entry was complete. If the participant responded “yes”, they continued on to answer additional questions regarding these movements. Participants could also report if they no longer owned their horse, which would result in their horse being removed from any additional monthly questionnaires. Participants who responded that their horse travelled during the month were asked to indicate the date(s) that their horse(s) left the home facility. For each chosen date, participants provided details on 1) the reason for travel, 2) the location of the destination (i.e., city/town), 3) the name of the destination, if available (e.g., name of the
facility), and 4) whether it was an overnight trip. Participants chose the reason for travel from a drop-down menu, which included the options of: competition, veterinary clinic, off-site lesson, race track, farrier, breeding, sales barn, leisure ride, performance/training clinic, and “other, please specify”. One monthly questionnaire was completed for each horse enrolled by the participant; however, the participant had the option to complete only one questionnaire if all of their horses had the exact same travel patterns during that month. A reminder email was sent to participants who did not complete a monthly questionnaire two weeks after the first invitation was sent. Participants were sent monthly invitations to the questionnaire regardless of their response (or non-response) to the previous month’s questionnaire.

5.3.4 Descriptive and statistical analyses

All data were cleaned to remove spelling errors, and were entered into a relational database in Microsoft Access 2016 (Microsoft Corporation, Redmond, WA, USA). The descriptive analyses of horse and home facility characteristics used the denominator data from the responses to the initial enrollment questionnaire. Descriptions of horse movement patterns were dependent on the participation rate each month. A movement was defined as an event where a horse was transported from one facility to a unique destination. A bidirectional movement occurred when a horse returned to their original location after reaching their unique destination location (e.g., location A to location B to location A). A unidirectional movement occurred when a horse did not return to their original location after reaching their unique destination (e.g., location A to location B). For the purposes of determining the total number of one-way directed movements between two facilities, bidirectional movements were considered as two unidirectional movements.
The statistical software packages Stata (StataCorp. 2013. Stata Statistical Software: Release 14. College Station, TX: StataCopr LP) and R (R Core Team. 2016. R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing) were used for all descriptive analyses. Graphs were produced using the “ggplot2” package in R. Statistically significant differences ($P < 0.05$) between variables with categorical outcomes were assessed using the Fisher’s exact test, and differences between variables with continuous outcomes were assessed using the Wilcoxon rank-sum test.

5.4 Results

5.4.1 Questionnaire response

A total of 222 participants completed the initial enrollment questionnaire and provided information on 570 horses (Figure 5.1). After completing the enrollment questionnaire, 23/222 (10.4%) owners were lost to follow-up (i.e., did not respond to any questionnaire invitations for the duration of the longitudinal study). On average, 3 horses (standard deviation (SD) = 2.5) were enrolled into the study per participant. There was no statistically significant difference in the number of horses enrolled per participant between owners that were lost to follow-up and owners that provided responses for the entire duration of the study ($P = 0.94$). Furthermore, there was no statistically significant difference in the time elapsed between completion of the initial enrollment questionnaire and the first monthly questionnaire (May) between owners that were lost to follow-up and owners that provided responses for the entire duration of the study ($P = 0.39$). The 23 owners that were lost to follow-up and their corresponding 63 horses were excluded from the analysis of the longitudinal study. In addition, 18 horses were excluded from the longitudinal study as their owners identified they no longer owned these horses prior to the
first monthly questionnaire. A final total of 199 owners and 489 horses and their movement patterns were included in the analysis of the longitudinal study.

Participation rates for each month of the longitudinal study are presented in Figure 5.1. Forty-four percent (87/199) of participants provided responses for all seven months. It is important to note that participants that responded for fewer than seven months were not considered lost to follow-up because responses occurred during select months of the study (i.e. they could respond one month, miss the second month, and respond the third month). There was no statistically significant difference in the number of horses enrolled per participant between those that responded and those that did not respond in a given month ($P > 0.05$ each month).

Throughout the 7-month period, 29/489 (5.9%) horses left the study (Figure 5.1). Seventy-nine percent (23/29) of horses that left the study did so for unreported reasons (i.e., owner simply indicated that they no longer owned that horse). There were no statistically significant differences in horse age ($P = 0.42$) or discipline ($P = 0.08$) between horses that remained in the study and horses that left the study.

5.4.2 Horse demographics

The average age of the participating horses was 12.2 years (SD = 6.4 years, median = 11.0 years, range = 6 months – 35 years). Fifty-five percent (312/570) of horses were geldings, 43% (244/570) were mares, and 3% (14/570) were stallions. The top two primary sport/competition disciplines captured in this study were hunter/jumper (19.8%, 113/570) and pleasure riding (17.4%, 99/570) (Table 5.1). When categorized, 63.3% (361/570) of horses participated in a competition discipline, 33.3% (190/570) of horses participated in leisure-related activities, and 3.2% (18/570) of horses participated in racing.
Within the 12 months prior to the study onset, participating horses were vaccinated against equine influenza (EI) (57.9%, 330/570), rabies virus (76.8%, 438/570), *Streptococcus equi* (strangles) (20.5%, 117/570), West Nile virus (WNV) (67.2%, 383/570), Eastern/Western encephalitis viruses (EEE/WEE) (52.1%, 297/570), equine herpesvirus (EHV) (46.7%, 266/570), and tetanus (79.5%, 453/570). Fourteen percent (81/570) of horses had not received any vaccinations in the past 12 months. The proportion of horses vaccinated against each pathogen varied depending on the primary sport/competition discipline of the horse (Figure 5.2). There was no statistically significant difference in age between vaccinated and unvaccinated horses for EI ($P = 0.80$), rabies virus ($P = 0.15$), strangles ($P = 0.70$), WNV ($P = 0.30$), EHV ($P = 0.72$), and tetanus ($P = 0.45$). Horses vaccinated for EEE/WEE were significantly older (mean = 12.7 years) than horses not vaccinated for EEE/WEE (mean = 11.6 years) ($P = 0.01$).

5.4.3 *Home facility characteristics*

The average number of horses boarded at a home facility was 17 (SD = 15, range = 1 – 104). Sixty-one percent (135/222) of participants reported that the horses at their home facility were owned by four or more owners, 15.3% (34/222) of participants reported that the horses at the facility were owned by two or three owners, and 23.9% (53/222) of participants reported that they were the sole owner of all horses at the facility. Eighty-two percent (183/222) of participants stated that there were senior horses (16 years of age or older) present at the home facility, 29.3% (65/222) indicated the presence of mares used for breeding purposes, and 25.2% (56/222) indicated the presence of foals.

Twenty-four percent (53/222) of participants stated that the horses boarded at their home facility competed in the same primary sport/competition discipline (e.g., they all were dressage
competition horses), while 76% (169/222) of participants stated that the horses boarded at their home facility did not compete in the same primary sport/competition discipline (e.g., some horses were dressage horses and some were hunter/jumper competition horses). Of the home facilities with a mixture of primary sport/competition disciplines, 16.6% (28/169) were a mix of two disciplines, 59.8% (101/169) were a mix of three disciplines, and 23.7% (40/169) were a mix of four or more disciplines.

5.4.4 Horse movements

A total of 3001 horse movements occurred throughout the duration of the study (Table 5.2). The proportion of horses that travelled per month ranged from 15.8% to 32.5% (Table 5.3). The total number of horse movements decreased over the duration of the study (Table 5.2). The average number of movements per horse, given that it travelled at least once during the month, increased between May and August, and then decreased between August and November (Table 5.3). From May to September, most movements were to attend a competition (34.5 – 46.9% of movements each month) (Figure 5.3). In October, most movements were for leisure rides (31.7%), and in November, most movements were to attend an off-site lesson (31.1%). Examples of “other” reasons for travel provided by participants included: letting their pasture grow, foxhunting, moving to a new home facility, community events/activities (e.g., horse drawn funerals, wagon rides, parades), house/horse sitting, visiting a friend, and cattle sorting. During the study period, 57.3% (51/89) of unidirectional movements were permanent moves to new home facilities; the majority of these movements occurred in May (33.3%, 17/51), October (21.6%, 11/51), and November (21.6%, 11/51).

While 98.3% (2951/3001) of the total movements over the 7-month period occurred
locally within Ontario, 0.5% (15/3001) of movements were to locations outside of Ontario (but within Canada), and 1.2% (35/3001) were international movements to the United States. Of the movements to the United States, 94.3% (33/35) were to attend a competition, and 5.7% (2/35) were to attend a performance/training clinic. The month with the largest number of international movements was June, where there were 12 movements to attend two competitions. These movements were made by four horses owned by one participant; one horse each attended a competition, and two horses attended both competitions. Of the movements to different provinces, 86.7% (13/15) were to attend competitions, and 13.3% (2/15) were to attend performance/training clinics.

5.5 Discussion

This study provides an overview of the descriptive characteristics of horses and horse facilities in Ontario. Horses that participated in competition and leisure disciplines had high vaccine coverage levels for the recommended “core” vaccines, which include vaccines for rabies virus, tetanus, and WNV (Wright and Kenney, 2004). In addition, reported vaccine coverage levels were higher in horses that participated in competition and leisure disciplines compared to horses that participated in racing. Although vaccine coverage levels for equine respiratory diseases such as EI and EHV have been previously reported during outbreaks in Ontario (Carman et al., 1997; Diaz-Mendez et al., 2010), the current study provides a comprehensive description of the vaccine profile of Ontario horses in a non-outbreak context. The findings of this study demonstrate that the proportion of horses vaccinated for EI and EHV was higher than previously reported (Carman et al., 1997; Diaz-Mendez et al., 2010).

Most participants reported that the horses boarded at their home facilities included a
mixture of primary sport/competition disciplines. Among Ontario horse owners, a commonly held belief has been that horses within the same discipline are frequently boarded together (personal communication, M. Barham, Animal Health Laboratory, University of Guelph). This anecdote has been used to support the idea that horses have reduced potential for contact with those participating in different disciplines. However, the results of this study demonstrate that 76% of home facilities boarded horses from different disciplines, suggesting that the connectivity between disciplines is higher than most horse owners perceive. Similar mixing between disciplines was observed in a survey of equine facilities in New Zealand, where only 57.1% of facilities kept horses for a single purpose (Rosanowski et al., 2012). This documented mixing between disciplines could contribute to opportunities for disease spread should a pathogen be introduced into horses of a single discipline.

Online questionnaires have been used in other equine populations to gather descriptive horse characteristics and horse movement patterns (Boden et al., 2013; Liebenberg et al., 2016). According to an industry-led study of Canadian horse owners in 2010, 89.2% of owners used the Internet, and 15.9% of those who did not use the Internet at that time expected to become users by 2011 (Equine Canada, 2010). This suggests that because almost 90% of horse owners were Internet users in 2010, a similar or higher proportion of owners would also be Internet users in 2015. The large proportion of Internet-users within the Canadian equine industry suggests that the use of an online questionnaire did not explicitly exclude potential participants who did not have access to the Internet.

Communication between participants and researchers has been previously demonstrated to increase participation during a longitudinal study, particularly due to an increased feeling of trust on the part of the participant (Hunt and White, 1998; Toledano et al., 2015). In the current
study, we provided participants with monthly updates on the study results, which is an effective tool for encouraging participant engagement (Hunt and White, 1998). The participation rate decreased around the mid-point of the study, but increased again as the study was concluding (Figure 5.1). The decrease during the mid-point of the study could be due to “survey fatigue”, where participants feel over-surveyed (Harcombe et al., 2011). Otherwise, a decrease in response rate could be attributed to other time commitments (e.g., family vacations). The drop in response rate suggests that the movement patterns reported during the mid-point of the study might not completely represent the true movement patterns.

The potential impact of selection biases should also be considered. It is possible that participants had an increased likelihood of joining the study due to their personal perceptions of the research (e.g., an owner’s perception that their horses are at greater risk for disease exposure due to travelling often), and therefore a volunteer bias might be introduced (Harcombe et al., 2011). However, the potential impact of volunteer bias is likely to be small, as individuals were recruited without regard to their individual travel patterns. The use of the monthly questionnaire attempted to decrease the possibility of recall bias, as it was thought that participants would be more likely to accurately remember their travel patterns within a shorter time frame. Recall bias could occur if individuals who travel often with their horse experienced difficulty recalling which trips occurred on which date(s). If recall bias was present, the accuracy of the timeline of movements would decrease, but the overall estimate of the number and frequency of movements would be unaffected. Loss to follow-up could have occurred if the participant decided that they no longer wanted to participate, or due to the inability of the researcher to contact the participant at the time of follow-up (Hunt and White, 1998). With an online questionnaire, it is difficult to determine the cause of loss to follow-up, as participants could leave the study for a variety of
reasons, including changing their email address. For this reason, it is also difficult to assess the characteristics of those that chose not to remain in study to evaluate the potential impact of either loss to follow-up or non-response biases.

The results of the 2016 Census of Agriculture estimated that there were 64,536 horses in Ontario (Statistics Canada, 2016). Using this number as a guideline, the 570 horses represented in this study is approximately 0.9% of the horses in Ontario. Nevertheless, this study provides the first comprehensive description of a subset of horses in Ontario, following the industry-led study of Canadian horse owners in 2010 (Equine Canada, 2010). It should be noted that horses in the racing industry were underrepresented in this study, and those that did participate were lost to follow-up after 2 months in the longitudinal study (no responses were received for race horses between July and November 2015). Due to the underrepresentation of race horses in this current study, further research is warranted to examine the movement patterns of horses within the racing industry.

While this study may not be representative of the entire horse population in Ontario, it provides insight into the descriptive characteristics of a group of horses and horse facilities in Ontario, in addition to a refined understanding of their movement patterns. Furthermore, this study provides comprehensive estimates of the vaccine coverage for various equine pathogens. Future research will explore the characteristics of highly connected horses and facilities using network analysis to determine potential risk factors for disease introduction and spread at different time points during the competition season. The empirical movement data collected in this study can inform further explorations of the potential for disease spread within the Ontario equine population.
5.6 References


Statistics Canada, 2016. Census of Agriculture, farms classified by the North American Industry Classification System (NAICS), every 5 years.


Table 5.1. Distribution of reported primary sport/competition disciplines of horses enrolled in a longitudinal study in Ontario, Canada.

<table>
<thead>
<tr>
<th>Discipline category</th>
<th>Discipline</th>
<th>Number (n = 570)</th>
<th>Percent (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Racing</td>
<td>Racing</td>
<td>18</td>
<td>3.2</td>
</tr>
<tr>
<td>Competition</td>
<td>Hunter/Jumper</td>
<td>113</td>
<td>19.8</td>
</tr>
<tr>
<td></td>
<td>Dressage</td>
<td>46</td>
<td>8.1</td>
</tr>
<tr>
<td></td>
<td>Eventing</td>
<td>42</td>
<td>7.4</td>
</tr>
<tr>
<td></td>
<td>Western pleasure</td>
<td>27</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>Driving</td>
<td>26</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td>Barrel racing/pole bending</td>
<td>28</td>
<td>4.9</td>
</tr>
<tr>
<td></td>
<td>Breed-specific competitions</td>
<td>21</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td>Reining</td>
<td>13</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>Halter/line classes</td>
<td>10</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>Gymkhana</td>
<td>9</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>Competitive trail riding</td>
<td>9</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>Other a</td>
<td>17</td>
<td>3.0</td>
</tr>
<tr>
<td>Leisure</td>
<td>Pleasure riding</td>
<td>99</td>
<td>17.4</td>
</tr>
<tr>
<td></td>
<td>Retired</td>
<td>42</td>
<td>7.4</td>
</tr>
<tr>
<td></td>
<td>Non-competitive trail riding</td>
<td>36</td>
<td>6.3</td>
</tr>
<tr>
<td></td>
<td>Other b</td>
<td>13</td>
<td>2.3</td>
</tr>
<tr>
<td>No response</td>
<td>--</td>
<td>1</td>
<td>0.2</td>
</tr>
</tbody>
</table>

a Participant responses include breeding, cutting, endurance, English and Western dressage, Extreme cowboy, foxhunting, and roping.

b Participant responses include cattle sorting, English and Western pleasure, flat work, yearlings in training, and therapy work.
Table 5.2. The number of bidirectional and unidirectional horse movements between May and November 2015, based on owner-completed monthly questionnaires during a longitudinal study in Ontario, Canada.

<table>
<thead>
<tr>
<th>Month</th>
<th>Bidirectional</th>
<th>Unidirectional</th>
<th>Total</th>
<th>Number (%) of total movements per discipline</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Competition</td>
</tr>
<tr>
<td>May</td>
<td>550</td>
<td>24</td>
<td>574</td>
<td>459 (80.0)</td>
</tr>
<tr>
<td>June</td>
<td>484</td>
<td>10</td>
<td>494</td>
<td>458 (92.7)</td>
</tr>
<tr>
<td>July</td>
<td>490</td>
<td>9</td>
<td>499</td>
<td>462 (92.6)</td>
</tr>
<tr>
<td>August</td>
<td>508</td>
<td>7</td>
<td>515</td>
<td>437 (84.9)</td>
</tr>
<tr>
<td>September</td>
<td>394</td>
<td>10</td>
<td>404</td>
<td>364 (90.1)</td>
</tr>
<tr>
<td>October</td>
<td>276</td>
<td>14</td>
<td>290</td>
<td>248 (85.5)</td>
</tr>
<tr>
<td>November</td>
<td>210</td>
<td>15</td>
<td>225</td>
<td>174 (77.3)</td>
</tr>
</tbody>
</table>

<sup>a</sup> The zeros within the racing discipline are due to owner non-response
Table 5.3. The number of horses that travelled each month, and the number of movements made per horse given that it travelled during the month, based on owner-completed monthly questionnaires during a longitudinal study in Ontario, Canada.

<table>
<thead>
<tr>
<th>Month</th>
<th>Travelled</th>
<th>Proportion travelled (%)</th>
<th>Number of movements per horse&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Yes</td>
<td>No</td>
<td>Mean (SD)&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>May</td>
<td>159</td>
<td>262</td>
<td>489</td>
</tr>
<tr>
<td>June</td>
<td>134</td>
<td>247</td>
<td>485</td>
</tr>
<tr>
<td>July</td>
<td>117</td>
<td>227</td>
<td>483</td>
</tr>
<tr>
<td>August</td>
<td>106</td>
<td>200</td>
<td>480</td>
</tr>
<tr>
<td>September</td>
<td>102</td>
<td>208</td>
<td>476</td>
</tr>
<tr>
<td>October</td>
<td>97</td>
<td>220</td>
<td>468</td>
</tr>
<tr>
<td>November</td>
<td>73</td>
<td>261</td>
<td>461</td>
</tr>
</tbody>
</table>

<sup>a</sup> The number of horses included in the study each month, after accounting for losses due to withdrawals (reported in Figure 5.1).

<sup>b</sup> The number of total unidirectional movements made by a horse, given that it travelled at least once during the month.

<sup>c</sup> SD = Standard deviation.
5.8 Figures

Figure 5.1. An overview of the longitudinal study design of horses in Ontario, Canada, including participation rates for each month between May and November 2015.
Figure 5.2. Proportion of horses vaccinated per primary sport/competition discipline category based on responses to the initial enrollment questionnaire (n = 570 horses, disciplines listed in Table 5.1). The “unsure” category represents the proportion of owners who were unsure of the vaccination status of the horse. Letters indicate statistically significant differences ($P < 0.05$) of pairwise comparisons using the Fisher’s exact test (a = leisure as referent, b = racing as referent).

Abbreviations: EI = equine influenza, WNV = West Nile virus, EEE/WEE = Eastern/Western encephalitis, EHV = equine herpesvirus.
Figure 5.3. The reason for horse movements on/off the home facility per month, based on owner-completed questionnaires during a longitudinal study from May to November 2015 in Ontario, Canada (n = 3001 movements).
CHAPTER SIX
Conclusions, limitations, and future directions

The objectives of this thesis were to investigate the opportunities for disease spread in the Ontario equine population, and to describe the implications for disease prevention and control. This research was identified as an important and necessary first step in addressing existing gaps in the understanding of potential disease spread in the Ontario equine population. This thesis involved a series of research projects to provide demographic details of horses in Ontario, the distribution of potential risk factors (e.g., age, vaccination status, and travel history), and the efficacy of commonly used biosecurity and infectious control measures.

First, the importance of sustained biosecurity and infection control measures was demonstrated using a model of an equine influenza outbreak in a simulated equine facility (Chapter 2). This chapter demonstrated the benefits of combining disease prevention and control strategies to minimize the impact of a disease outbreak at the facility-level. Second, the contact structure of horses associated with a single equestrian show was investigated to describe the potential for disease spread resulting from movements on/off their home facility (Chapter 3). The observed horse contact network was used to develop an agent-based model to evaluate the effectiveness of biosecurity and infection control measures applied prior to and following the equestrian show (Chapter 4). Finally, the demographics and movement patterns of horses enrolled in a longitudinal study were described to improve the understanding of the characteristics of the Ontario horse population (Chapter 5).

This concluding chapter focuses on a summary of the key findings and recommendations from this thesis, the limitations of the approaches used, and the opportunities for future research.
6.1  Summary of key findings

6.1.1  Current use of disease prevention strategies

Horse owners at a two-day silver-level dressage show reported that their horse(s) were highly vaccinated (Chapter 3). Horses had received vaccines for pathogens such as equine influenza (96%), rabies virus (90%), Streptococcus equi (strangles) (60%), West Nile virus (88%), Eastern/Western equine encephalitis (85%), equine herpesvirus (73%), and tetanus (83%). In addition, horse owners reported a reduction in the opportunities for horse contact (e.g., direct nose-to-nose contact, and sharing equipment, cleaning tools, or water/feed) as they travelled away from their home facility with their horse. These findings demonstrate that horse owners are knowledgeable about the potential exposure to pathogens due to direct horse-to-horse contact and shared items, and that they are actively using prevention measures to reduce the risk of infection.

Owners of horses enrolled in the 7-month longitudinal study (Chapter 5) reported high vaccine coverage levels for the “core” vaccines recommended by the Ontario Ministry of Food, Agriculture, and Rural Affairs, which include rabies virus (77%), tetanus (80%), and West Nile virus (67%) (Wright and Kenney, 2004). When stratified by sport/competition discipline, competition horses had significantly higher vaccine coverage levels for equine influenza, rabies virus, Eastern/Western equine encephalitis, equine herpesvirus, and tetanus, compared to race horses. In addition, competition horses had significantly higher vaccine coverage levels for equine influenza and equine herpesvirus compared to leisure horses. While vaccination is not required to participate in all competition/sporting events in Ontario, it is recommended for horses that travel frequently (Ontario Ministry of Agriculture Food and Rural Affairs, 2013). These findings suggest that horse owners recognize the importance of vaccination and are currently
using it as an infection prevention strategy for their horses.

6.1.2 Benefits of combining disease prevention and control strategies

The combined usage of multiple biosecurity and infection control measures can aid in disease prevention and control within equine facilities. Using an agent-based model of an equine influenza outbreak in a simulated equine facility, a combination of increased initial vaccine coverage prior to the outbreak and a reduction in horse-to-horse contact during the outbreak was the most effective strategy to minimize the projected attack rate (Chapter 2). This finding suggests that implementing a combination of disease prevention measures (e.g., vaccination) during day-to-day operations, in addition to disease control measures (e.g., reducing horse-to-horse contact) in the event of an outbreak, could be used as an effective disease management strategy.

In a simulated equine influenza outbreak within a network of horses associated with a single equestrian show, a relative comparison of intervention effectiveness supported the combined usage of disease prevention and control measures (Chapter 4). A 14-day quarantine period implemented when horses attending the show returned to their home facility was the most effective intervention, resulting in a 93% reduction in the average attack rate. Quarantine for shorter time periods (2 or 5 days) was also effective when combined with targeted increases in initial facility-level vaccine coverage. These findings suggest that a 14-day quarantine period would be best to recommend in instances when high vaccine coverage levels in a facility cannot be achieved (e.g., adverse reactions to vaccine products or unknown vaccination history). Alternatively, if a long quarantine period would not be possible to implement, it would be best to recommend a high facility-level vaccine coverage to reduce the impact of any potential disease
6.1.3 Connectivity of horses in Ontario

Horses participating in this research travelled frequently and exhibited a high degree of connectivity. The network of horses associated with a single equestrian show included 69 horses that attended the show, and 710 horses that did not attend the show, but shared a home facility with the show attendees (Chapter 3). Previous studies within the UK and Australia have demonstrated the potential for contact between horses attending an equestrian show (Christley and French, 2003; Bell and Drury-Klein, 2011; Firestone et al., 2011); however, this was the first known published quantification and visualization of a contact network of Ontario horses. The results of this study could be used by equestrian show organizers to inform the design of event stabling locations. For example, organizing stabling locations so that horses cannot contact one another when present in the same location could limit the extent of potential disease spread.

The longitudinal study provided insight into the travel patterns of 469 horses from May to November 2015 (Chapter 5). Participating horses travelled frequently, with a total of 3001 directed one-way trips occurring during the study period. This research provides the first characterization of long-term horse movements patterns in Ontario, which contributes to the understanding of the connectivity within the population. Furthermore, the longitudinal study demonstrated that home facilities exhibited a mix of horses from different disciplines (racing, leisure, and competition), as 76% of participants reported that horses from a variety of disciplines boarded at their horses’ home facility. This suggests that potential contacts between disciplines may be facilitated due to mixing at home facilities, in addition to the potential contacts within disciplines that may be facilitated as horses attend the same events. The potential
for contact between disciplines has implications in the event of an outbreak, as this finding suggests that using a horse’s discipline as an identifier for contact tracing would underestimate the number of horses at risk.

6.1.4 Importance of collecting empirical contact and movement data

Empirical contact and movement data can be used to better inform the use of disease prevention and control strategies in populations where disease spread is influenced by underlying contact patterns. In combination with mathematical modeling, the incorporation of an empirical contact structure provided a refined estimate of intervention effectiveness in a population of horses associated with an equestrian show (Chapter 4). Planning disease intervention strategies without the explicit consideration of the contact structure in a population could under- or over-estimate the resources required to control a large outbreak in the population (Webb, 2006). Empirical movement data collected from horses enrolled in a longitudinal study highlighted the potential connections that could be facilitated by their movements (Chapter 5). The horse movement data collected during the completion of this thesis could be used to support future research to examine and refine disease prevention, control, and surveillance strategies while considering the network structure within the Ontario equine population.

6.2 Limitations

Due to the nature of the approaches used in this thesis, several limitations were anticipated. First, the absence of existing data describing the Ontario equine population posed challenges for data collection. A convenience sample was used to collect data from horse owners at the dressage show (Chapter 3) and for enrolling owners into the longitudinal study (Chapter 5)
due to the absence of a central registry-type list from which individuals could be sampled. While equine traceability in Canada has been previously identified as a priority by Equine Canada and the Canadian Food Inspection Agency (Equine Canada, 2010), it has not yet been implemented. The absence of a traceability program provided further difficulties in the collection of horse movement data due to the reliance on the completion of monthly questionnaires from participating horse owners (Chapter 5). The types of sampling used in this research have the potential to introduce biases, particularly volunteer bias and non-response bias. Unfortunately, without further information on the source population (i.e., all horses/horse owners in Ontario), the potential extent and impact of these biases cannot be addressed.

Furthermore, the use of questionnaires for data collection presents the potential for recall and loss to follow-up biases. For the first questionnaire (Chapter 3), participants completed the questionnaire on-site and did not have access to their horses’ records to answer questions regarding their previous travel patterns and vaccination histories. Some questions were designed to minimize recall bias by providing categories for participants to select an answer (i.e., questions about the number of owners per facility and the average range of horses transported on/off the facility per month). Similarly, the monthly follow-up times for the longitudinal study (Chapter 5) were designed to minimize the potential for recall bias, as it was thought that participants would be more likely to accurately remember their travel patterns within a shorter time frame. In both instances, it is possible that individuals who travelled more frequently with their horse might have been less precise in their estimate of how many times they travelled and/or which travel instances occurred on which date(s). This would underestimate the true travel patterns of horses in Ontario if highly travelled individuals only accurately recalled the date(s) on which a significant event happened (i.e., a large competition). Missing data due to loss
to follow-up during the longitudinal study (Chapter 5) might cause a similar potential for bias. However, loss to follow-up would only impact the results of this study if the loss-to-follow up was differential with respect to the exposure and outcome of interest. Any missing data caused by loss to follow-up would underestimate the connectivity and travel patterns within the population. It is important to note that while these biases are possible, the results generated from this thesis represent an essential first description of the demographic and movement data of the Ontario equine population.

There are some limitations inherent to mathematical modeling that should also be discussed. Agent-based models were used to synthesize the information collected from questionnaires in order to inform the investigations into the potential for disease prevention and control. However, the models provide an oversimplified representation of the natural history of equine influenza, which may influence the impact of the tested interventions. It was necessary to make assumptions and simplifications due to the absence of required empirical data, including within-facility contact rates, vaccine coverage, and vaccine efficacy. These assumptions highlight areas where improved data collection is warranted to better understand the Ontario equine population.

Lastly, the extent of generalizability should be discussed. As the conclusions drawn from this research are based on contact and movement data collected from only a subset of horse owners within Ontario, the estimated potential for disease spread, prevention, and control may not be representative of the entire Ontario equine population. Certain findings, such as measures calculated from network analysis, are specific to the situation in which the data were originally collected. In addition, it should be noted that horses in the racing industry were underrepresented in this study, and therefore conclusions specific to race horses cannot be made. Because of this
limitation, further research is warranted to examine the movement patterns of horses within the racing industry. Despite the limitations discussed above, the consistencies among the conclusions drawn from multiple chapters in this thesis lends support to the usefulness of the results.

6.3 Opportunities for future research

This thesis contributed to an improved understanding of the potential for disease spread, prevention, and control in the Ontario equine population, and it also highlights opportunities for future research in the following areas:

- **Information on prevalence and incidence of equine diseases in Ontario.** There are few available estimates of the prevalence and incidence of various equine diseases in Ontario, which limits the ability to incorporate these data as input parameters for mathematical models. The absence of data presents additional difficulties in determining which diseases are a high priority for more targeted disease prevention, surveillance, and control strategies.

- **Further investigations of the impact of horse movements on disease spread.** While this thesis provides preliminary insight into the impact of horse movement patterns on the potential for disease spread, further research is warranted to investigate network characteristics of highly connected horses and facilities. In addition, the horse movement network could be used to parameterize mathematical models to further investigate targeted disease surveillance and control strategies.

- **Improved understanding of within-facility contact patterns.** The mathematical model used to investigate disease spread in horses associated with a single equestrian show was parameterized using the observed between-facility contact patterns. In this model, it was
necessary to make assumptions about the within-facility contact patterns in the absence of more detailed data. However, further research should examine the appropriateness of the homogeneous mixing assumption within facilities.

- **Additional data on the efficacy of biosecurity and infection control measures.** While the impact of vaccination, reduced horse-to-horse contact, and quarantine were studied in this thesis, it would be beneficial to determine the efficacy of additional measures used to prevent and control disease. In particular, the use of mathematical models to study indirect transmission for relevant pathogens would provide an opportunity to test biosecurity and infection control measures designed for preventing indirect spread, such as sanitation, hand-washing, and changing clothes/shoes.

- **Ability and willingness of horse owners to implement disease prevention and control strategies.** The ability and willingness of horse owners to implement recommended disease prevention and control strategies is an essential area for future research. For example, some equine facilities may not be equipped with the infrastructure to implement the necessary quarantine recommendations. In addition, horse owners with high-level competitors (i.e., horses that travel often to compete) might not be able to quarantine their horse for long periods of time upon return to their facility. The attitudes of horse owners towards the implementation of disease prevention and control strategies, as well as potential alternatives in the event that they cannot be implemented, should be addressed.

### 6.4 Concluding remarks

This thesis provides an overview of the potential for disease spread in the Ontario equine population, and describes the implications for disease prevention and control. It provides the first
insight into the characteristics and the connectivity of horses in Ontario, as well as empirical evidence which supports the benefits of biosecurity and infection control measures. The outcomes of this thesis can be used to inform the use of disease management strategies that reduce the adverse health and economic consequences of disease within the equine industry. In addition, the results of this thesis can assist knowledge-users, such as horse owners and veterinary practitioners, to determine which measures would be most effective for the prevention and control of disease during an outbreak. Describing the demographics of Ontario horses, and the relationships created as they travel, is a fundamental step towards further explorations of the potential risk of disease within the population.

6.5 References


2.1.15).


doi:10.1017/S095026880500467X

Supplementary Figure 2.1. Results of the calibration experiment fitting the model-projected outbreak by least squares estimation to a previously reported outbreak by Morton et al. (2011). The best feasible model projection used a contact rate of 4.86 contacts per day to fit to the previously reported outbreak curve.
Supplementary Figure 2.2. Demonstration of the effect of the waning immunity distribution used in the agent-based model of an equine influenza outbreak in a simulated equine facility.
Horses are a highly mobile population. Many horses move frequently to participate in equestrian shows and events, and movement patterns are highly variable. The movement of horses is one of the most important factors determining the risk of the potential introduction and spread of an infectious disease within this population.

### EXPECTED OUTCOMES

This pilot study will provide us with a snapshot of the nature and extent of horse movements and the network of potential contacts associated with a single equestrian show in southern Ontario. Our results will help us to further refine and develop our survey in order to initiate a larger version of this project in 2015.

**Research results will help us to:**

1. Design and target risk-based surveillance programs and control measures to prevent the spread of equine diseases among horses in Ontario.
2. Improve our ability to quickly detect and control potential outbreaks of equine disease in Ontario.
3. Minimize the economic and emotional impact that equine disease can have on the equine industry, and Ontario farm families.
4. Improve the health and welfare of Ontario horses.

### PILOT STUDY DESIGN

- The research team will be present at the show.
- Participants will be asked to provide informed consent to participate in the survey. All information provided will remain confidential.
- Participants will complete a 2 page survey documenting information about their horse such as, the number of events attended over the course of the past year, travel distances, type of “home” facility, and the number of horses at the “home” facility.
- Participants will submit the completed forms to a sealed box on-site at the event.
- To recognize the time taken to complete the survey, participants will receive a $10 Tim Horton’s gift card.

### FOR MORE INFORMATION

Dr. Amy Greer, BSc MSc PhD  
Tier II Canada Research Chair in Population Disease Modeling and Assistant Professor  
Department of Population Medicine, Ontario Veterinary College, University of Guelph  
Email: agreer@uoguelph.ca  
Telephone: 519-824-4120 extension 54070  
Website: www.mathepiLab.org
INFORMED CONSENT FORM

Study Title: Using social network analysis to develop an understanding of the opportunities and challenges for infection control in equine populations.

Investigators and Funding Organization
You are being asked to participate in a research study conducted by Dr. Amy Greer (Tier II Canada Research Chair in Population Disease Modeling and Assistant Professor) and Dr. Terri O’Sullivan (Assistant Professor), Ontario Veterinary College at the University of Guelph. This study is funded by the Canada Research Chairs program and NSERC. If you have any questions or concerns about the research, please feel free to contact Amy Greer (agreer@uoguelph.ca, 519-824-4120 extension 54070).

Study Purpose
The purpose of this project is to develop a snapshot of the nature and extent of horse movements and the network of potential contacts associated with a single equine show. Our preliminary results will help us to refine and develop our survey in order to initiate a larger version of this project in 2015. You may not directly benefit from this research; however, we hope that your participation in the study may help to:

1. Design and target risk-based surveillance programs and control measures to prevent the spread of equine diseases among horses in Ontario.
2. Improve our ability to quickly detect and control potential outbreaks of equine disease in Ontario.
3. Minimize the economic and emotional impact that equine disease can have on the equine industry, and Ontario farm families.
4. Improve the health and welfare of Ontario horses.

If you agree to take part in this study, you will be asked to complete the survey on the next 2 pages. This survey will ask about your horse, your horses “home facility” and your horses travel patterns. The survey will take you approximately 15 minutes to complete. Your answers in this study will remain confidential. We will minimize any risks to breach of confidentiality. Only the principal investigators (Amy Greer and Terri O’Sullivan) and their team will have access to the survey results. Your name will not be attached to the survey, making it difficult to link your name with your survey responses. Research materials will be stored securely at the University of Guelph and paper copies will be shredded after 7 years. No identifying information will be included in any presentation or publication resulting from this research.

Payment for participation
In recognition of your time and contribution to this research project you will receive a $10 Tim Horton’s gift card.

Your participation in this study is completely voluntary and you can withdraw at any time. You are free to skip any question you choose.

This study has been reviewed and received ethics clearance through the University of Guelph Research Ethics Board (REB#14AP021). If you have questions regarding your rights as a research participant, please contact:

Research Ethics Coordinator
University of Guelph
437 University Centre
Guelph, ON N1G 2W1

Telephone: (519) 824-4120, ext. 56606
E-mail: sauld@uoguelph.ca
Fax: (519) 821-5236

By proceeding to the survey on the next page you are indicating that you have read and understood this consent form and agree to participate in this research study. Please keep this page for your records and return the survey to the researchers. Please DO NOT write your name on the survey.
Questionnaire

SURVEY

PLEASE DO NOT PUT YOUR NAME ON THIS SURVEY.

1. How old is your horse? __________

2. What is the sex of your horse (circle one)? Mare / Gelding / Stallion

3. What is your entry number for this event? ______________
   (This is to ensure that we don’t have duplicate submissions for a single horse and will not be linked to your personal information).

4. Is your horse being stabled on-site at this event? Yes / No
   If yes, barn # __________, aisle # __________ and/or stall # __________

For the purpose of this survey the term “home facility” refers to the facility that your horse spends the majority of time at.

5. What are the first 3 letters of your home facility postal code? ______________
   If you do not know, please provide the name and town of your home facility so that we can look up the postal code for you. ______________

6. What best describes your home facility? Check all that apply.
   □ facility has more than 4 horse owners
   □ facility has 3 or fewer owners
   □ only my own horses on the facility (1 owner for all horses)

7. How many horses are boarded at your home facility (including your own)? __________

8. On average, how many new horses (e.g. for training, shows, new boarders, breeding etc.) enter your home facility per year? ______________

9. What types of horse contact occurs when your horse is stabled at your home facility? (Check all that apply).
   □ direct nose-to-nose contact with other horses
   □ sharing of equipment (e.g. bridle)
   □ sharing of cleaning tools (e.g. muck fork)
   □ shared water/feed (e.g. buckets or troughs)
   □ shared wash rack
   □ no contact
   □ unsure

10. On average, how many resident horses are transported on and off the facility per month where they will have contact with other horses? (Check the answer that best describes the horse movement)
    □ 1-5 horses
    □ 6-10 horses
    □ 11-15 horses
    □ 16-20 horses
    □ 21 or more horses
SURVEY

11. In the past 12 months has your home facility housed any of the following (check all that apply)?
   □ breeding mares
   □ foals
   □ senior horses (16 years old or older)

12. Are other horses from your home facility participating in this event? Yes / No
   □ If Yes, how many? ____________
   □ If Yes, are the other horses from your home facility stabled in neighboring stalls? Yes / No

13. In the previous 6 months, how many times did you travel with this horse away from your home facility (e.g. training, veterinary care, event, show, race etc.)? ____________

14. In the next 6 months, how many times did you plan to travel with this horse away from your home facility (e.g. training, veterinary care, event, show, race etc.)? ____________

15. In the previous 12 months, what is the maximum number of nights that your horse was stabled in a location other than your home facility (e.g. away at an event)? ____________ nights

16. What types of horse contact occurs when your horse is stabled away from your home facility (e.g. away at an event)? (Check all that apply).
   □ direct nose-to-nose contact with other horses
   □ sharing of equipment (e.g. bridle)
   □ sharing of cleaning tools (e.g. muck fork)
   □ shared water/feed (e.g. buckets or troughs)
   □ shared wash rack
   □ no contact
   □ unsure

17. Do you ever travel with this horse internationally (i.e. out of Canada)? Yes / No
   □ If Yes, how many times per year? ____________

18. In the past 12 months, has this horse been vaccinated against any of the following? Please check all that apply.
   □ equine influenza (flu)
   □ rabies
   □ strangles
   □ west nile virus (WNV)
   □ eastern/western encephalitis (EEE/WEE)
   □ equine herpes virus (rhino)
   □ tetanus
   □ other (e.g. Potomac horse fever) ________________________________
   □ none
   □ don’t know
Appendix III Supplementary materials for Chapter Four

Supplementary Table 4.1. Initial conditions used to parameterize the agent-based model of horses associated with an equestrian show in Ontario, Canada.

<table>
<thead>
<tr>
<th>Facility</th>
<th>Total horses per facility</th>
<th>Number of attending horses</th>
<th>Boarding location of attending horses</th>
<th>Initial vaccine coverage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15</td>
<td>4</td>
<td>S1</td>
<td>40</td>
</tr>
<tr>
<td>2</td>
<td>9</td>
<td>1</td>
<td>SB1</td>
<td>44</td>
</tr>
<tr>
<td>3 b</td>
<td>30</td>
<td>2</td>
<td>SB2, SI c</td>
<td>37</td>
</tr>
<tr>
<td>4</td>
<td>11</td>
<td>1</td>
<td>SI</td>
<td>36</td>
</tr>
<tr>
<td>5 b</td>
<td>50</td>
<td>1</td>
<td>SB2</td>
<td>36</td>
</tr>
<tr>
<td>6</td>
<td>12</td>
<td>3</td>
<td>SI</td>
<td>42</td>
</tr>
<tr>
<td>7 b</td>
<td>26</td>
<td>4</td>
<td>SB1</td>
<td>38</td>
</tr>
<tr>
<td>8 b</td>
<td>33</td>
<td>1</td>
<td>SB1</td>
<td>36</td>
</tr>
<tr>
<td>9</td>
<td>10</td>
<td>1</td>
<td>SB1</td>
<td>40</td>
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<td>10</td>
<td>6</td>
<td>1</td>
<td>SI</td>
<td>50</td>
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<tr>
<td>11</td>
<td>18</td>
<td>1</td>
<td>SI</td>
<td>39</td>
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<td>12</td>
<td>10</td>
<td>3</td>
<td>SB2</td>
<td>40</td>
</tr>
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<td>13</td>
<td>6</td>
<td>1</td>
<td>SI</td>
<td>50</td>
</tr>
<tr>
<td>14 b</td>
<td>34</td>
<td>1</td>
<td>SB1</td>
<td>38</td>
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<td>SB2</td>
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<td>2</td>
<td>SB2</td>
<td>43</td>
</tr>
<tr>
<td>22</td>
<td>12</td>
<td>1</td>
<td>SB2</td>
<td>36</td>
</tr>
<tr>
<td>23 b</td>
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<td>SB1</td>
<td>40</td>
</tr>
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<tr>
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<td>42</td>
</tr>
<tr>
<td>25</td>
<td>70</td>
<td>2</td>
<td>SB2</td>
<td>36</td>
</tr>
<tr>
<td>26</td>
<td>7</td>
<td>1</td>
<td>SI</td>
<td>40</td>
</tr>
<tr>
<td>27</td>
<td>12</td>
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<td>SI</td>
<td>37</td>
</tr>
<tr>
<td>28</td>
<td>12</td>
<td>2</td>
<td>SB1</td>
<td>43</td>
</tr>
<tr>
<td>29</td>
<td>6</td>
<td>1</td>
<td>SI</td>
<td>42</td>
</tr>
<tr>
<td>30</td>
<td>20</td>
<td>1</td>
<td>SB1</td>
<td>42</td>
</tr>
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<td>31</td>
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<td>1</td>
<td>SB2</td>
<td>50</td>
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<td>1</td>
<td>SB2</td>
<td>40</td>
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<td>33</td>
<td>8</td>
<td>1</td>
<td>SB2</td>
<td>38</td>
</tr>
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<td>34</td>
<td>18</td>
<td>2</td>
<td>SI</td>
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<td>SB1</td>
<td>40</td>
</tr>
<tr>
<td>36</td>
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<td>1</td>
<td>SI</td>
<td>50</td>
</tr>
<tr>
<td>37</td>
<td>25</td>
<td>1</td>
<td>SI</td>
<td>36</td>
</tr>
<tr>
<td>38</td>
<td>11</td>
<td>1</td>
<td>SB1</td>
<td>36</td>
</tr>
</tbody>
</table>

^a The boarding locations at the competition venue included stabling barn #1 (SB1), stabling barn #2 (SB2), and the daily ship-ins (SI).

^b Facilities identified as large facilities (>= 20 horses) for sensitivity analysis.

^c One horse was boarded in the coverall and the other was boarded in the field.
**Supplementary Table 4.2.** Home facilities within each category of the vaccination intervention in the agent-based model.

<table>
<thead>
<tr>
<th>Risk factor</th>
<th>Category</th>
<th>Facilities a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of horse owners per facility</td>
<td>Only 1 owner</td>
<td>13, 17, 28, 36</td>
</tr>
<tr>
<td></td>
<td>2 or 3 owners</td>
<td>2, 10, 15, 19</td>
</tr>
<tr>
<td></td>
<td>4 or more owners</td>
<td>1, 3, 4, 5, 6, 7, 8, 9, 11, 12, 14, 16, 18, 20, 21, 22, 23, 24, 25, 26, 27, 29, 30, 31, 32, 33, 34, 35, 37, 38</td>
</tr>
<tr>
<td>Average number of boarding horses moved on or off the home facility per month</td>
<td>1 to 5 horses</td>
<td>2, 4, 6, 8, 9, 11, 12, 13, 14, 15, 17, 18, 19, 22, 24, 26, 27, 28, 29, 31, 33, 34, 35, 36, 38</td>
</tr>
<tr>
<td></td>
<td>6 to 10 horses</td>
<td>1, 5, 7, 37</td>
</tr>
<tr>
<td></td>
<td>11 to 15 horses</td>
<td>10, 16, 21, 23, 25</td>
</tr>
<tr>
<td></td>
<td>16 to 20 horses</td>
<td>3, 20, 30, 32</td>
</tr>
</tbody>
</table>

a Facilities listed by their identification number provided in Supplementary Table 4.1.
**Supplementary Table 4.3.** The proportion of home facilities within each risk factor category in the agent-based model.

<table>
<thead>
<tr>
<th>Number of horse owners per facility</th>
<th>Number of horses moved on/off the home facility per month</th>
<th>1 – 5</th>
<th>6 – 10</th>
<th>11 – 15</th>
<th>16 – 20</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>2 or 3</td>
<td></td>
<td>3</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>4+</td>
<td></td>
<td>18</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>30</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>25</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>38</td>
</tr>
</tbody>
</table>
Supplementary Figure 4.1. Summary of the outcomes of interest in the base case scenario of the agent-based model. All panels describe the results of 1000 simulation runs. A. Model-projected attack rate. B. Outbreak duration. C. Number of facilities with at least one infected horse during the outbreak. D. Average effective reproductive number (Re).
Supplementary Figure 4.2. Boxplots of the projected outbreak duration in the intervention scenarios. The top left graph represents the results of the base case scenario in the absence of any interventions. The last three graphs of the left column represent the results of the quarantine scenario alone. The top middle and right graphs represent the results of the targeted vaccination scenarios alone. The bottom and top of each box represent the 25\textsuperscript{th} and 75\textsuperscript{th} percentiles, respectively, and the horizontal line within the box represents the median. Each box represents 1000 simulation runs.
**Supplementary Figure 4.3.** Boxplots of the projected equine influenza attack rates in the scenario with a random proportion of home facilities targeted for increased facility-level vaccine coverage, compared to home facilities targeted for increased facility-level vaccine coverage based on the number of horse owners per facility. The bottom and top of each box represent the 25th and 75th percentiles, respectively, and the horizontal line within the box represents the median. Each box represents 1000 simulation runs.
You are being invited to participate in a research study conducted by Kelsey Spence (Master’s student), Dr. Amy Greer (Tier II Canada Research Chair in Population Disease Modeling and Assistant Professor), and Dr. Terri O’Sullivan (Assistant Professor), Ontario Veterinary College at the University of Guelph. This study is funded by Equine Guelph. If you have any questions or concerns about the research, please feel free to contact Amy Greer (agreer@uoguelph.ca, 519-824-4120 extension 54070).

Study Purpose
The goals of this project are to understand the nature and extent of horse movements in Ontario, as well as to determine the connections between horses over the summer 2015 season. You may not directly benefit from this research; however, we hope that your participation in the study may help to:

1. Design and target risk-based surveillance programs and control measures to prevent the spread of equine diseases among horses in Ontario.
2. Improve our ability to quickly detect and control potential outbreaks of equine disease in Ontario.
3. Minimize the economic and emotional impact that equine disease can have on the equine industry and Ontario farm families.
4. Improve the health and welfare of Ontario horses.

Study design
In order to participate in this study, you must be an Ontario resident and over the age of 18 years. If you agree to take part in this study, you will be asked to complete an enrollment questionnaire about your horse, your “home facility”, and the horses permanently stabled at your “home facility”. The questionnaire will take you approximately 5 minutes to complete. We will ask you for your first name and your email address, which will be used to correspond with you between May 2015 and November 2015. Every month, you will receive an email asking you to complete a short survey (requiring less than 10 minutes) about where your horse traveled that month.

Your answers in this study will remain confidential and we will minimize any risks to breach of confidentiality. However, please note that confidentiality cannot be guaranteed while data are in transit over the Internet. No identifying information will be included in any presentation or
publication resulting from this research.

Compensation for participation
In recognition of your time and contribution to this research project, your name will be entered into a draw for 3 prizes worth approximately $1000 total. Your chance of winning depends on the number of people who participate in the study, but are approximately 1 in 67. Each month that you fill out a response to the survey, you will receive an additional entry into the draw. Please note that you may be required to submit a SIN number in order to collect prizes.

Your participation in this study is completely voluntary and you can withdraw at any time. You are free to skip any question you choose. If at any point during your involvement in the research study you decide you would no longer like to participate, you are free to close the survey window without submitting your responses.

This study has been reviewed and has received clearance through the University of Guelph Research Ethics Board (REB #15FE013). If you have questions regarding your rights as a research participant, please contact: Director, Research Ethics; Telephone: (519) 824-4120, ext. 5660; email: sauld@uoguelph.ca.

By continuing to the next page, you are indicating that you have read and understood the information about the questionnaire and agree to take part in this study. By providing your email address, you are providing consent to receive monthly emails between May 2015 and November 2015.

You are encouraged to print this document for reference.
Enrollment questionnaire

1. Are you at least 18 years of age and currently residing in Ontario?
   - Yes
   - No

   If the participant answers “No”, the questionnaire will conclude and display the message:
   “Thank you for your response. Unfortunately, you are not eligible to participate. Only
   individuals 18 years of age or older and residents of Ontario are eligible to participate at
   this time.”

2. What is your first name and email address? This will be used to correspond with you over the
   course of the summer.
   - First name: _____________
   - Email address: _____________
   - Confirm email address: _____________
   - I do not have an email address

   If the participant chooses “I do not have an email address”, the following question will
   appear:

   Please provide your first name and phone number so we can correspond with you.
   - First name: _____________
   - Telephone number: _____________

3. If you have more than one horse, would you like to provide answers for all of your horses?
   - Yes
   - No
   - I do not have more than one horse

   If the participant chooses “Yes”, Questions 4 and 5 will be displayed. If the participant
   chooses “No” OR “I do not have more than one horse”, the questionnaire will
   automatically skip to Question 6.

4. How many horses do you have?
   - 1
   - 2
   - 3
   - 4
   - 5
   - 6
   - 7
   - 8
   - 9
   - 10 or more
The number of horses that the participant chooses will determine the number of fields in Questions 5 to 9. For example, if they indicate that they have three horses, there will be three fields in each question to provide answers for the horses.

5. Would you like to enter the names of your horses, or provide nicknames? This may help you keep track of which horses you are providing answers for in future surveys.
   - Name: ____________
   - More fields will appear to correspond with the number of horses that the participant selects

6. What is the primary sport/competition discipline for your horse?
   - Racing
   - Dressage
   - Hunter / Jumper
   - Eventing
   - Western pleasure
   - Driving
   - Breed-specific competitions
   - Halter / line classes
   - Barrel racing/ pole bending
   - Reining
   - Gymkhana
   - Competitive trail riding
   - Non-competitive trail riding
   - Pleasure riding
   - My horse is retired
   - Other, please specify: __________

7. How old is your horse (in years)? __________

8. What is the sex of your horse?
   - Mare
   - Gelding
   - Stallion

9. At the time of this questionnaire, is your horse currently vaccinated (i.e. has been vaccinated in the past 12 months) against any of the following? Please check all that apply.
   - Equine influenza (flu)
   - Rabies
   - Strangles
   - West Nile Virus (WNV)
   - Eastern/western encephalitis (EEE/WEE)
   - Equine herpes virus (rhino)
   - Tetanus
   - Other, please specify: ______________
   - None
o Don’t know

For the purpose of this questionnaire, the term “home facility” refers to the facility that your horse spends the majority of time at.

10. What are the first three digits of your home facility postal code? ________
   o If you do not know, please provide the name, town, and/or website address of your home facility so that we can look up the postal code for you.
     o Name: ____________
     o Town: ____________
     o Website: ____________

11. What best describes your home facility?
   o Facility has more than 4 horse owners
   o Facility has 3 or fewer owners
   o Only my own horses on the facility (1 owner for all horses)

12. How many horses are permanently housed at your home facility (including the horse(s) you have provided answers for)? __________

13. Do all of the horses at your home facility participate in the same discipline?
   o Yes
   o No

If the participant selects “Yes”, Question 14 is displayed. If the participant selects “No”, they Question 15 is displayed.

14. The horses at your home facility participate in which discipline?
   o Racing
   o Dressage
   o Hunter/Jumper
   o Eventing
   o Western pleasure
   o Driving
   o Breed-specific competitions
   o Halter/line classes
   o Barrel racing/pole bending
   o Reining
   o Gymkhana
   o Competitive trail riding
   o Non-competitive trail riding
   o Pleasure riding
   o The horses are retired
   o Other, please specify: _______________

15. What are the top three primary disciplines for horses at your home facility?
Most horses at my home facility participate in: *(drop-down menu)*
- Racing
- Dressage
- Hunter/Jumper
- Eventing
- Western pleasure
- Driving
- Breed-specific competitions
- Halter/line classes
- Barrel racing/pole bending
- Reining
- Gymkhana
- Competitive trail riding
- Non-competitive trail riding
- Pleasure riding
- The horses are retired
- Other

Some horses at my home facility participate in: *(drop-down menu)*
- Racing
- Dressage
- Hunter/Jumper
- Eventing
- Western pleasure
- Driving
- Breed-specific competitions
- Halter/line classes
- Barrel racing/pole bending
- Reining
- Gymkhana
- Competitive trail riding
- Non-competitive trail riding
- Pleasure riding
- The horses are retired
- Other

A few horses at my home facility participate in: *(drop-down menu)*
- Racing
- Dressage
- Hunter/Jumper
- Eventing
- Western pleasure
- Driving
- Breed-specific competitions
- Halter/line classes
- Barrel racing/pole bending
- Reining
- Gymkhana
o Competitive trail riding
o Non-competitive trail riding
o Pleasure riding
o The horses are retired
o Other

16. In the past 12 months, has your home facility housed any of the following? Check all that apply.
   o Breeding mares
   o Foals
   o Senior horses (16 years old or older)
   o None of the above
Monthly questionnaire – Example for participants with one horse

Welcome! Thank you for your continued voluntary participation in our equine study at the Ontario Veterinary College, University of Guelph. This is your survey for the month of May 2015. As you know, every time you submit your response (and for each horse that you provide answer for), your name will be entered into a draw to win 1 of 3 tack shop gift cards worth approximately $1000 total! If you have decided to no longer participate, you can withdraw your consent at any time.

Did your horse leave your home facility for any duration of time this month?

- Yes
- No
- I no longer own this horse

If the participant answers “Yes”, they continue onto the next screen. If the participant answers “No” or “I no longer own this horse”, the questionnaire is complete and displays the message “We thank you for your time spent taking this survey. Your response has been recorded.”
Please choose the date(s) that your horse left the home facility this month.

- May 1
- May 2
- May 3
- May 4
- May 5
- May 6
- May 7
- May 8
- May 9
- May 10
- May 11
- May 12
- May 13
- May 14
- May 15
- May 16
- May 17
- May 18
- May 19
- May 20
- May 21
- May 22
- May 23
- May 24
- May 25
- May 26
- May 27
- May 28
- May 29
- May 30
- May 31

The selected date(s) will populate the options on the next screen.
The options in the drop-down list under “Reason for travel” include: competition, veterinary clinic, off-site lesson, race track, farrier, breeding, sales barn, leisure ride, performance/training clinic, and other.
Monthly questionnaire – Example for participants with two horses (same design for 3 to 10 horses)

The horse names are populated based on the participant’s response in the enrollment questionnaire. If the participant selects “Yes” for both horses, they continue onto the next screen. If the participant selects “Yes” for only one horse, they will move directly to screen 4 (the date selection). If the participant selects “No” or “I no longer own this horse”, they will not provide answers for that horse. If the participant selects “No” or “I no longer own this horse” for both horses, the questionnaire is complete and displays the message “We thank you for your time spent taking this survey. Your response has been recorded.”
Did both horses have exactly the same travel patterns? This would mean that every time they left the home facility this month, they went to the same place on the same day(s).

- Yes
- No

*If the participant selects “Yes”, they will move to the next screen, but will only complete the question once for both horses. If the participant selects “No”, they will move to the next screen, and will complete the question once for each horse.*

Please choose the date(s) that **Jackson** left the home facility this month.

- May 1
- May 9
- May 17
- May 25
- May 2
- May 10
- May 18
- May 26
- May 3
- May 11
- May 19
- May 27
- May 4
- May 12
- May 20
- May 28
- May 5
- May 13
- May 21
- May 29
- May 6
- May 14
- May 22
- May 30
- May 7
- May 15
- May 23
- May 31
- May 8
- May 16
- May 24

*The selected date(s) will populate the options on the next screen.*
The options in the drop-down list under “Reason for travel” include: competition, veterinary clinic, off-site lesson, race track, farrier, breeding, sales barn, leisure ride, performance/training clinic, and other.