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An Agent-based Approach for Modelling Spatial Transmission Processes of Foot-and-mouth Disease in Korea 2010-11

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ABSTRACT

Background: On 28th November 2010, an outbreak of foot-and-mouth disease (FMD) occurred in Andong, Korea. Despite evacuation of people and animals in adjacent areas, the FMD virus spread to 75 cities in 11 provinces during this outbreak. This study argues that FMD is an infectious disease which is transmitted in a non-linear and non-prescriptive pattern by interactions of agents and external environments.

Aims and Methods: This study aims to identify the dominant factors of the interaction between agents and their external environments that affect FMD transmission. The specific objectives of this research are: 1) To analyse the spatial distribution and transmission path of FMD, 2) To investigate cause-and-effect relationships that affect spatial spread of FMD, 3) To explore potential factors influencing the spatio-temporal risk of FMD transmission based on agent based model. To accomplish each goal, cartographical analysis, case and control study, and agent based model are used as a method.

Results: The spatial distribution of FMD shows that most cases were concentrated in Gyeonggyi, Gangwon, and Gyeongbuk provinces. Subsequently, the spatial processes of FMD transmission show the entire procedure of FMD epidemic in 6 phases, and they explain the reasons of infection at each phase. Results of case and control study show that the logistic model was in a good fit, and odds of having the factor ‘farm density’, ‘road proximity’ and ‘temperature change’ was significantly higher than for control farms. Putting these factors (adding ‘highway proximity’) as parameters, the agent based simulation shows that human movement and external environments affect the velocity of disease transmission. A two level simulation is implemented, which is sensitivity (individual) analysis and combination analysis. Results of the sensitivity analysis are ‘temperature change’ and ‘farm density’ as the major factors. Results of combination analysis are a mixture of low temperature and high livestock density have potential risk for FMD transmission.

Conclusion: This study demonstrates the role played by agents and external environments that affect FMD transmission during the 2010-11 Korean epidemic. This study observes the movement of individuals as well as external environments influence the velocity and the dimension of the epidemic. Results provide insights into understanding of the risk factors associated with FMD transmission, and the results are useful to prevent FMD transmission in the future. It is therefore crucial that further disease control strategies must pay attention to the various factors driving disease outbreaks. There is a need to understand the contributions of the different factors to the epidemiology of infectious diseases. Further improvements to this approach would help model and analyse the risk of disease spread.

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1. INTRODUCTION

1.1. Background and Objectives of Study

Veterinary epidemic outbreaks of diseases in animal population have caused disasters in livestock communities across the world for centuries. These animal diseases, which include Foot-and-Mouth Disease (FMD), give serious constraints on dairy industry, market chain, and the global economy (Convery *et al.* 2008, Dion and Lambin 2012, OIE 2012). According to the World Organisation for Animal Health (OIE), FMD occurred in 76 countries on 4 continents from 2010 to 2012, leading to almost 20,000 animal deaths (OIE 2012). As World Animal Health Information Database (WAHID) reports, 75% of Asian countries and 63% of African countries are struck by FMD in spite of vaccine and slaughtering implement policy (See appendix 1 and 2). From these facts, we can identify FMD as a pandemic issue, which spreads beyond national boundaries.

The cross-boundary infections of FMD virus had impacts on Korea. The latest epidemic occurred in 28th November 2010 in Andong city and had spread to 75 cities. As a result, approximately 150,000 cattle and 3,310,000 pigs were slaughtered (QIA 2011). Evidence from QIA (2011) suggested that the FMD transmission was caused by the following reasons: initially, the local government's failure to handle the outbreak at an early stage; secondly, high livestock density due to the lack of farming space in Korea; thirdly, easy transmission of the virus through road networks; and finally, the cold weather during that time obstructed the government's preventive measures. The institution indicated that the transmission vectors were identified as vehicles (61%), livestock owners (15%), infected individuals nearby (12%), outsiders (8%) etc. Therefore, it is assured that the last FMD epidemic in South Korea results from vector interactions with persistently transmitted viruses.

Recent studies in animal disease fields have examined issues that dealt with Korean FMD (Yoon et al. 2006, Lee 2010, QIA 2011, Yoo 2011, Park and Bae 2012, Choi et al 2012). These works can be categorized into two types. The former studies are composed of report-based, virus-central, and epidemiological results, in other words *pro hoc* studies. While, the latter studies are method-based work, using GIS, spatial statistics, and other simulation in order to predict the outbreak and progress of FMD. Moreover, veterinary science (Bessell *et al.* 2008, Yoo 2011, Muleme 2012, Muroga *et al.* 2013) and disease ecology (Carrel and Emch 2013) show the process and risk of FMD infection.

Previous studies, however, have not reported an actual relationship between agents and FMD transmission. First, although *pro hoc* studies have values as a historical record, these studies cannot suggest prevention strategies for the future disease that could damage the nation's society, economy, and environment. Second, previous studies ignore spatial interaction among individual agents. However, FMD virus usually infects animals and transmits through geographical space, and therefore space plays a significant role in the dynamics of the FMD (Liliana and Suzana 2009). Third, there are limitations in methodologies. GIS and spatial statistics can display the transmission result but cannot express the process of transmission. Moreover, these can work only with data on a global scale. Therefore, these methods have limitations to explain virus transmission on an individual level. Fourth, although animal disease is as important as human disease, previous studies in geography overlook this issue. After the mid 90's, people started to give interests on human and animal disease studies, especially on livestock and categories like domestic or nature. Animal disease in geography may well explain the interactions and circumstances of infections between humans and animals, and it is highlighted as a new field in geography (Convery *et al.* 2008).

Taking advantage of complexity theory, recent studies of infectious disease of animals try to explain spatial interactions among agents (Liliana and Suzana 2009, Lambin *et al.* 2010, Dion and Lambin 2012, Del Valle, Mniszewski, and Hyman 2013). It is worthwhile to study epidemics in complexity theory, because this theory incorporate the structure of interaction between actors, scale, centrality, and linkage of network as causes of disease emergence (Yoon and Chae 2005). However, it would have been better if there were spatial and environmental factors, such as distance, environment condition in the system. Actually, by considering these issues, it would possibly be powerful to analyse and interpret disease spread through various locations (Lambin *et al.* 2010, Dion and Lambin 2012, Wu 2013).

Therefore, the purpose of this study is to examine the impact of spatial interaction factors between agents and environment on 2010-11 FMD transmission. These objectives are comprehensively analysed through as follows:

1) To examine the spatial transmission process and factors of 2010-11 FMD epidemic

2) To investigate risk factors associated with FMD epidemic

3) To discover the impact of potential factors that influence FMD transmission speed based on an agent based model

This study describes the FMD model and its implementation for the outbreaks that could happen in South Korea. The author develop a method based on the agent-based approaches in complexity networks, rather than using a GIS clustering methodology in order to explain the process of disease transmission from individual to global scale. The author would also like to discover the spread of disease caused by the agents of spatial dynamics.

1.2. Organisation of the Study

This paper consists of six chapters. Subsequent to chapter 1, chapter 2 reviews existing literature regarding various perspectives on FMD and FMD virus, applying spatial diffusion theory on infectious disease, and showing studies related to agent-based model. The Review starts with previous studies of veterinary, followed by disease ecology, spatial diffusion theory, studies of agent based models, and limitations in the existing research. This chapter supports reasons why this topic is worth to be studied.

Chapter 3 examines spatial progress and factors that affect FMD. The datasets are composed of human and natural environments which are from KOSIS (Korean Statistical Information Service), KOSTAT (Statics Korea), and KAHIS (Korea Animal Health Integrated System). Using ArcGIS 10.1, this chapter will first analyse the spatial progress of FMD transmission, and then analyse factors of FMD outbreak points.

Chapter 4 investigates risk factors associated with FMD transmission. Based on the results of spatial analysis and additional datasets, logistic regression was used to extract significant factors that are related to FMD transmission. This analysis also provides strengths among factors. The selected factors are used as parameter for chapter 5.

Chapter 5 discovers the impact of determinant factors that influence spatial and temporal risk to FMD transmission based on agent-based model. In the procedure, sensitivity analysis is initially implemented and then combination between factors are conducted afterwards. In this chapter, various scenarios will show temporal records of epidemic and its emergence.

In chapter 6, the author summarizes the key findings once again and draws a conclusion with contributions and limitations of this work, and will give suggestions for future studies.

This research constructs the synthetic framework that accounts for FMD transmission based on four steps. The current study initially obtains data from various sources (e.g., KOSIS, KOSTAT), displays spatial data, and selects factors using spatial analysis and logistic regression. Results from empirical data are then put to agent based method for simulation. The conceptual framework is shown below (Figure 1).

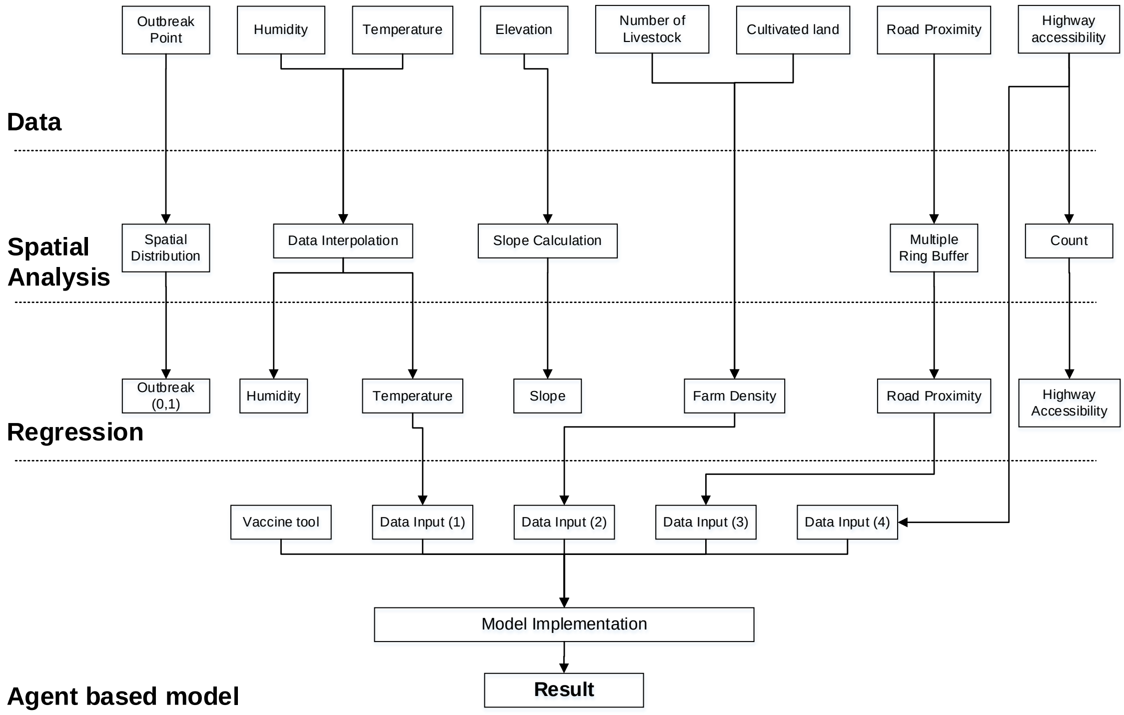


Figure 1. The Conceptual Flowchart of Thesis

2. LITERATURE REVIEW

A recent scope of the work done in social sciences is partly in the realm of animal disease. The genetic character of individuals has been used in veterinary science to understand molecular structure, and in disease ecology to understand disease transmission in an external environment. To understand FMD, it is necessary to understand the location and environment of person and place (Hunter 1974, Meade and Emch 2010). Although epidemic diseases were examined by early medical geographers, their studies were not focused on animals or animal pathogen genetics. For medical geographers, however, spatial spread of animal diseases holds a great potential for answering questions about how nature and society interact within a landscape to produce patterns of animal health.

The purpose of this chapter is to review recent studies in various fields related to FMD virus and diffusion theory. Also, the author aims to apply animal epidemic issue to agent based model, which are one of the multi-agent system (MAS), and to discover how this model demonstrates disease diffusion in a best way.

2.1. Various Approaches of FMD Transmission

2.1.1. Perspectives of Veterinary Science

FMD is defined as a highly infectious disease that affects cloven-hoofed ruminants, such as cattle, pigs, sheep, goats, and deer. The small, pathogenic organism of FMD is called *Picornaviridae*, the prototypic family of the genus *Aphthovirus* (the same family as the common cold virus, Rhinovirus) (Convery *et al.* 2008). The Animal and Plant

Quarantine Agency in Korea (농림축산검역본부) classified FMD virus into 7 serotypes (A, O, C, Asia1, SAT1, SAT2, SAT3) and 80 subtypes. There is a large difference between each serotypes. It does not neutralize its characteristics, and it cannot be cured by vaccine due to its genetic and antigenic features.

When this contagious virus flows into an animal, the animal eventually suffers badly or dies after a lot of blisters running on its buccal epithelial cell, breast, nasal bridge, and hoof with a body temperature increased. It is commonly transmitted through direct contact between infected and susceptible animals. The OIE announced this disease as an A (highly risk) class disease, and likewise the Korean government designated FMD as a first class livestock contagious disease (Animal and Plant Quarantine Agency).

Since 2000, there were three cases before 2010 epidemic: 15 cases in 2000, 16 cases in 2002, and 17 cases between January and May 2010. FMD epidemic in 2000 and 2002 was a ME-SA (Middle East-South Asian) O serotype, Asia A serotype occurred in January 2010, and SEA (South East Asia) O serotype in November 2010. From appendix 1 and 2, we estimate various serotypes from each continents (i.e. the serotype of A and O are spread through the Asian countries while O, SAT1, SAT2 increase in the Africa continent)

In spite of the spatial heterogeneity of FMD, there are common features of FMD outbreak. Generally speaking, the seasonal emergence of FMD is between summer and autumn, which is approximately from June to October (Green, Kiss, and Kao 2006, EUFMD 2009). FMD cases occurred in UK, Mid-East, Africa, and Asia have almost the same period (Green, Kiss, and Kao 2006, Lee 2010)

The severe FMD virus transmits rapidly through respiratory such as nose or mouth virus. In veterinary science, the FMD virus transmission is categorized into four different paths (QIA 2011). The first path is a *direct transmission* by making contact with blister fluid of an infected animal or saliva, milk, scar, sperm, breathing air, feces, otherwise by food products. The FMD virus can maintain its infectivity from 6 - 8 days to 210 - 352 days, due to its resistibility of FMD virus depending on animal types, temperature of storage (frozen or cool) (Domingo *et al.* 1992, Chou and Yang 2004). Park *et al.* (2013) and Yoo (2011) notified that animals within short distances interact with each other, and as temperature decreases, FMD virus begins to infect animals with a weak immune system.

Second, *indirect transmission* happens through contact with wool, hair, grass or straw, footwear, clothing, livestock equipment or vehicle tyres etc. The FMD virus can survive between 24 and 36 hours in one's nose and larynx. Moreover, one individual is not allowed to have contact with any animal within susceptible livestock or laboratory for at least 7 days because the virus on clothes or wheels could infect another individual within three weeks (Park *et al.* 2009). Recent outbreaks have mostly transmitted indirectly through domestic livestock. This fact means that domestic livestock, which has high density and potential for virus emergence, have also a high possibilities of the diffuse of virulence (Rivas *et al.* 2003, Verma *et al.* 2008). Several studies indicated that road proximity to farms and dairy truck networks have a correlation on FMD occurrence (Rivas *et al.* 2003, Kao *et al.* 2007, Convery *et al.* 2008, Muroga *et al.* 2013).

Third, *rodents, birds, insects, cats, dogs, and wild animals* can transmit virus in contacting secretion waste in infected farms easily. Although FMD do not influence wild animals directly, they can act as mechanical vectors, just like humans do. Moreover, avian species are not susceptible to infection, however they can carry the virus on their feathers or feet (Brian 2012). Thus, all of these species can carry the virus even though their role in dissemination is uncertain.

Fourth, the disease can be transmitted by the *airborne effect.* Mainly, the virus moves to far places by droplet nuclei, where climate and topography plays an important role (Alexandersen *et al.* 2003, Mikkelsen *et al.* 2003, Brown, McLafferty, and Moon 2009).

The National Veterinary Research & Quarantine Service reports that FMD virus can affect up to 60km on land and 250km on sea, but Donaldson *et al.* (2001) and Alexandersen (2003) indicated that this virus could be blown to different places where relative humidity is over 60%and wind constantly blows in free convection. For airborne diseases, wind velocity as well as direction is a significant factor for transmission (reconstructed by Yoo (2011)). Results from QIA (2011) report there was no airborne transmission in 2010-11 epidemic, but we still have to consider climate and topologic barriers as the previous study has emphasised.

FMD virus transmission speed differs to animal species. Pigs exhale a large amount of airborne virus (10^3TCID50) which is three times bigger than the amount of cattle and sheep (10TCID50) (Alexandersen *et al.* 2003, Mikkelsen *et al.* 2003). Intriguingly, pigs are infected only through oral route while cows are most likely infected on the respiratory route (Donaldson 1972, Donaldson, Lowe, and Ward 2002). Donaldson *et al.* (2002), who was interested in this difference, simulated the possibility of FMD virus transmission by placing one thousand animals in a 6km distance. As a result, cows had a high possibility of infection whereas pigs were *vice versa*. However, beyond the high density of livestock breeding system in Korea and joint management between pig farm and cattle farm, it is hard to examine disease diffusion by each animal type.

Incubation period, same as latency time, is justified as *"a period taken by the multiplying organism to reach a threshold necessary to produce symptoms in host"* (Wikipedia). The incubation period of FMD virus varies to serotype and dose of the virus, transmission route, sensitivity between animal species. Sellers and Forman (1973) insisted that clinical sign of FMD was checked after 2 to 14 days on direct contact, and airborne spread on farm-to-farm takes 4 to 14 days. Alexandersen *et al.* (2003) and Yoo (2011) argued that farm-to-farm direct contact and airborne spread both have approximately 2 to 14 days of incubation period, but it can be shorten to 6 days depending on flock density. All of the numbers were verified by Alexander (2003a, 2003b). Rivas *et al.* (2003) noticed that FMD virus can reproduce within 2 to 3 days, and infected animals disseminate virus to other animals and other sites before clinical alert operates.

Synthetically, veterinary fields distinguish FMD transmission in 4 types: direct transmission, indirect transmission, wild animal transmission, and airborne transmission. QIA (2011) and Park *et al.* (2013) suggested that the presence of FMD in Korea was an indirect vector-borne disease. Powerful reasons are movements of people (e.g., traveling veterinarian, inseminating technician). Evidence was proved in 2010 epidemic in which transmission were resulted from traveling vets and livestock owners. Moreover, there was an investigation where coconuts, imported hays, and contact of wild animals were referred as an indirect transmission medium. However, this probability was very low. Possibilities of airborne disease resulted low inferred to topological barrier (Lee 2010).

2.1.2. Perspectives of Disease Ecology

The basic idea of disease ecology is that human life is a process, a continual interaction between internal and external environments (Carrel and Emch 2013). On that account, disease ecologists concern human behaviours, concern their cultural and socio-economic context, and concern interactions with the environmental conditions that accelerate disease transmission (Meade and Emch 2010). In terms of this idea, disease is a result of complex interactions (imbalance) between the triad of the agent, the host, and the environment. Climate change, population growth, urbanization, and agriculture migration may give positive or negative effects to disease transmission.

This theorem equally adapts to animal diseases. Disease ecology on livestock animals also focus on animal behaviours, agents, and external environments. Surprisingly, these animals are strongly related to human behaviour. For example, FMD pathogens occurred in UK and South Korea and they had spread rapidly due to human transmission (Lee 2010, Oh 2011, QIA 2011), and the geographic spread of Swine flu virus (H1N1) 2009 and SARS 2003 was determined by a combination of human mobility, and interactions of human and air networks (Smith *et al.* 2009, Bajardi *et al.* 2011, Belik, Geisel, and Brockmann 2011). From these examples, it is acknowledged that the ecology of livestock is greatly influenced by human movement. Thus, it is easy to understand that the ecology of animal disease is relevant to human behaviour.

Epidemiological triangle

The epidemiologic triangle depicts the interaction of agents, hosts, and environmental factor that varies on circumstances of each group of infected animals (Ewald and Burch 1994, Thrusfield 2013). This model applies to biological, chemical, and physical agents. For a disease to outbreak, the basic elements of virus and a link of transmission triangle must be present. The disease occurs when an agent with a virus meets a host which is vulnerable to the agent in a specific environment. Environments determine the condition of the agents and host for interaction and transmission. Here are some details of the epidemiologic triangle (Ewald and Burch 1994, CDC 2012, Thrusfield 2013).

Agent is the cause of the disease, the real answer of 'what and who causes the disease?'. Bacteria, virulence, fungi, protozoa and so other biologic beings could be an example. Host factors include humans and animals which are exposed and move the disease. Examples are listed as previous exposure, vaccination status and response, age, gender, behaviour, genetics, resilience. Finally, environment variable encompasses various aspects of natural and social conditions, such as animal stocking density, animal mobility between groups, environmental conditions (e.g., temperature, humidity, wind velocity and direction, precipitation), and housing (e.g., ventilation, sanitation) (Carrel and Emch 2013).

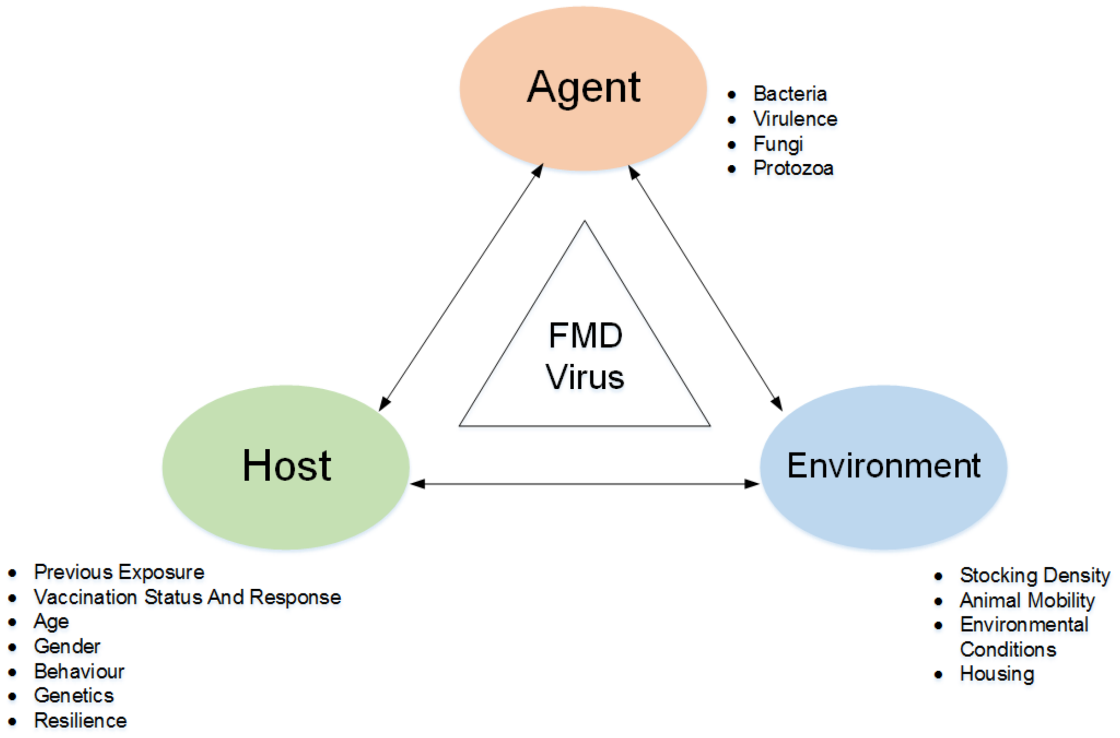


Figure 2. The Epidemiologic Triad Concept (source adapted from Carrel and Emch 2013)

Disease outcomes are results of place and time specific interactions among these variables. To understand FMD in South Korea, agent, environment, and host variables are shown in figure 2. Human agent contributes the most to influenza transmission in combination with transportation patterns and the livestock density. In addition, weather patterns in the winter also reflect this influenza risk and transmission. Interactions among three variables are not statistic, but they underlie a dynamic and complex system. Dubos (1987), and other ecologists stressed that "*nature is not a constant entity but rather is a passing place that organism have adapted to*". His insight gives us that disease spreads when animal host, pathogens, and various vectors meet and interact with each other, or it is disturbed by environmental and social barriers.

2.2. Animal Disease in Spatial Diffusion Theory

2.2.1. Fundamentals of Diffusion Theory

There are two means how infectious diseases could be found in a specific location: One way is that the pathogen is developed spontaneously and the other is that it is moved there from another place (Meade and Emch 2010). Generally, we use the latter meaning as diffusion. The term “diffusion” is a pattern which spread or transmit from a point or beginning place (Saint-Julien 2004, Meade and Emch 2010). Geographers usually define spatial diffusion theory, or the geography of diffusion, as a spread of all processes that describe the movements of goods, people, innovations, or ideas within a given area through time (Angulo *et al.* 1980, Saint-Julien 2004, Brown, McLafferty, and Moon 2009). Various events on all spatial levels from climate variations to vehicles, houses, schools, and hospitals are involved in diffusion processes. Most diffusion studies belong to the field of quantitative statistics and spatial computing science, where collaborations between different geographical locations are mainly studied in many publications (Park and Bae 2012, Carrel and Emch 2013, Gaudart *et al.* 2013).

Primary questions of spatial diffusion theory are: What is being carried? How are things carried across space? Who or what is the carrier? What kinds of things get in the way? These questions also apply to the key questions of disease transmission.

One of the important facts for diffusion studies is discovering several types of diffusion. Each type has its discriminated definition but they have a strong link to each other. Initially, *Relocation diffusion* is a spatial distribution process because the infection spreads into a new area and it leaves its source behind. It often leaps over long distances and massive populations. Some historical influenza epidemics have taken this form.

Contagious diffusion (or contact, expansion diffusion) is an infection spread by direct contact. The disease is being diffused, remains or develops, in the place of origin, but new areas are also infected as time passes. A contagious microorganism transmits from one individual to another within some physical proximity (Sabel, Pringle, and Schærström 2009, Meade and Emch 2010). A measles epidemic is a clear example. *Hierarchical diffusion*, as a final type, is a phenomenon in which infection spread through a class or group, for instance where it begins in a large settlement and gradually spreads out to progressively smaller ones. The spread of HIV/AIDS from larger to smaller centres in the United States would be an example of this. In classical studies, contagious disease diffusion model follows a hierarchical neighbourhood model, which starts from a place, and then spreads as humans interact in space (Sabel, Pringle, and Schærström 2009). Its diffusion starts from a specific place to neighbouring places based on their proximity. Nowadays, however, transport of epidemic or pandemic diseases are non-linear due to massive increase of airline capacity (Gatrell 2005).

2.2.2. Infectious Disease Studies in Diffusion Theory

Torsten Hägerstrand (1967) primarily insisted current theory of spatial diffusion. In this study, he discovered spatial diffusion of automobile ownership through southern Sweden and the adoption of agricultural subsidies and of tuberculosis tests for cattle. Hägerstrand analysed with a Monte-Carlo simulation method producing patterns which displayed similar to the case points. After Hägerstrand's establishment of diffusion theory, sociologists, economists, and psychologists as well as geographers conducted numerous studies. Although there were some criticisms, Hägerstrand's study gave an insight to later studies. Focused on infectious disease, diffusion theory has two approaches: detailed empirical studies of disease transmission within local places and mathematical and statistical modelling according to a stochastic formulation.

Empirical studies of disease transmission

Empirical studies of disease transmission are significant to medical geographers. In empirical studies, diffusion theory could help identify where, when, why, how the disease emerges. As a matter of fact, many empirical studies about disease transmission are incorporated to other fields, and most of them are only related to ecology. Roundy (1978) described the importance of human mobility in determining exposure to pathogens or the introduction of pathogens from one location to another, or disease diffusion. Angulo *et al.* (1985) examined the empirical evidence of smallpox diffusion in primary schools in which diffusion agencies operated was well characterized in time, space, persons and number of attacks.

Empirical studies about animals are concerned as well (Convery *et al.* 2008, Kim 2011b). Convery *et al.* (2008) identified FMD as a disastrous disease to farms, tourists, habitats, and the national economy, of which memories, experiences, and daily troubles were shared by people who experienced the disease in 2001. This interdisciplinary work was done by sociologists, ethnographers, and geographers. Kim (2011) criticized the failure of vaccine policy implemented from the South Korean government in terms of risk management perspective. FMD civil investigation team raised a problem to the government's FMD crisis management after investigation found out that the burial site is not safe and that there was a problem with the spill of leachate.

Computational modelling

Compared to empirical studies, computational models for infectious disease studies have been used to gain insights for the transmission process of epidemics. Several approaches have been worked out in geography, such as spatio-temporal studies and network studies. In spatio-temporal studies, understanding spatial interactions and adapting time-space to infectious disease is a significant tradition (Carrel and Emch 2013). Cliff and Haggett (1988) used this theory to link epidemic models to better demonstrate the flow of contagious disease through time and space. In this study, Cliff and Haggett (1988) used Iceland as a closed laboratory to investigate measles and influenza diffusion processes. Applied models related to the basic SIR model are used to observe measles' epidemic. Despite not using sensitivity analysis of the model, it gives geographical modellers an insight to forecast epidemic patterns by adding seasonal components and strengthening the inter-regional basis.

Network studies basically concern the sources of disease diffusion that may spread through nodes and links. The sources are expressed as points, lines, and areas. Buchanan (2003) noted that networks are prone for spreading and maintaining infections, whatever virulence the infective agent might possess. Thus to stop the disease from spreading, we have to discover what the connectors are. In other words, if the structure of the network changes, the spread can be halted. Most of the network studies are performed with statistical methods, and people in fields related to geography used GIS tools to visualize the results.

Choi *et al.* (2012) analysed the network process, particularly about FMD transmission. The critical point in this study is (i) indicating outbreak location (ii) calculating transmission period in road network from outbreak location (iii) output the result of transmission velocity. Using network analysis, this study reproduced the diffusion of FMD disease by comparing road network and Euclid distance. Choi *et al.* (2012) pursued to calculate FMD transmission period and velocity by analysing road network method, yet did not justify the comparison between road and Euclid distance. Another weakness about this particular study is that the results are only based on technical tools. So, it didn't consider significant factors of infectiousness, such as livestock density, distance from livestock and road, distance from residential area. This study contributes to set up preventive measures against FMD epidemics, after considering a problem about the current 20km defence zone criteria.

Ortiz-Pelaez *et al.* (2006) discuss the movement of cattle and sheep during the 2001 FMD outbreak in the UK, using social network analysis. Ortiz-Pelaez *et al.* (2006) aimed to analyse three different outbreak assumptions that the infection was only spread by the movements in social networks: no spread, spread up to 7%, and around 25%. Multiple directed dichotomized networks which were affiliated with three hierarchical clusters were analysed. It is noticed that the networks of betweenness, connectivity, and centrality can affect infectious disease in the context of network analysis, yet if this network is detected epidemiologically, it could be a valuable tool in the control of infectious disease outbreaks and early warning system.

Since FMD virus usually spreads on a geographical space, it is expected that space plays a significant role in the dynamics of the FMD (Liliana and Suzana 2009). During this substantial outbreak, not only are there a lot of agents that influenced the disease but also spread in dynamic routes (Donaldson, Lowe, and Ward 2002, Kim 2011a). Recent evidences from South Korea, China (Zhong *et al.* 2003), and United Kingdom (Haydon, Woolhouse, and Kitching 1997, Keeling 2005, Kao *et al.* 2007) enlighten us that infectious disease spreads in a geographical pattern. On account of this, it is vital to understand complex dynamics of contagious disease in certain spatial environments (Liliana and Suzana 2009, Lambin *et al.* 2010).

2.3. Agent Based Models of Disease Transmission

2.3.1. Key Factors of Complexity Theory

Before this study highlights agent-based model, it is essential to mention the complexity theory which is the background theory of this paper. Complexity theory anticipates that such systems may display in an unstable way (Gatrell 2005, Curtis and Riva 2010). 'Complexity paradigm' is about "relationships that cannot be reduced to simple linear models or their variants" (Gatrell 2005), or called as "the clash of Reductionism" (Giampietro 2004). Mostly, this system is thought as an open system in interaction with the environment (Gatrell 2005). The complexity theory has been discussed in various fields. Generally in social science, transport networks moves people and goods from one place to another. In terms of health context, elements of a virus might spread within from local to global region (Gatrell 2005). These elements are composed of the virus itself, infected and susceptible individuals, transport systems etc. (Gatrell 2005, Carrel and Emch 2013).

According to Gatrell (2005), complexity system differs from traditional general system in four aspects. Firstly, large numbers of elements are interacting dynamically across networks. Watts (1999) and Barabasi and Frangos (2002) argued that in a complex universal puzzle, lots of pieces are connected, interact, and caused by others in different events. Secondly, the social system follows the non-linearity rule. A change in one element does not directly change another individual. A small change can cause a large effect. Each element is 'ignorant' of the behaviour of the system as a whole, thus we cannot sum or add the behaviour of each individual. Thirdly, interactions within system elements can make an emergence of a new structure. In this process, self-organisation makes a result of shift and change of their internal structure spontaneously and adaptively in order to cope with their environment (Cilliers 2002). Authors insist that macro-level patterns are resulted from micro-level behaviours. Finally, Gatrell (2005) noted that complexity theory involves both human and non-human agents. Likewise, Urry (2003) argue that nowadays social events are related with hybrids of physical and social relations. Such hybrids include health, technologies, environment, Internet and so on.

In particular, geographical research on health and disease concerns with the processes and relationships in space and time that manage human (animal) interactions with their environment in complex and non-linear ways (Curtis and Riva 2010). Curtis and Riva (2010) insisted that health geography continues to develop ways to study interactions between processes which operates at different socio-geographical scales. Moreover, Gatrell (2005) agreed to this idea by adding the wider context of economic, political, social, and environmental changes.

Health geographers equally pay attention to complex spatio-temporal relations, from global to local scale, as we can see the impact of diseases that occurs in one part of the world rapidly spreads to a different place and extend in size (Gatrell 2005, Kiss, Green, and Kao 2006, Curtis and Riva 2010). Especially, connectivity as well as distance are important for contagious disease. Today, diseases like HIV/AIDS, SARS (severe acute respiratory syndrome), swine flu, and FMD have rapidly infected highly linked major cities around the world as a result of air travel (Gatrell 2005). As Buchanan (2002) argued, such networks are therefore prone to the spreading and the persistence of infections, therefore the implication is that the connectors have to be targeted. In a meanwhile, scholars from complexity network studies argue that 2001 FMD in Britain was a 'scale free network' disease (May and Lloyd 2001, Shirley and Rushton 2005, Kao et al. 2007). That is, the speed of FMD transmission depends on node (farm)-centrality, scale, and distance between nodes rather than random spread (May and Lloyd 2001, Shirley and Rushton 2005, Kao et al. 2007).

2.3.2. Representative Method in Complexity Theory: Agent Based Model

There are numerous agents in the ecosystem, and these multiple agents interact through their organization (Bousquet and Le Page 2004). These agents, eventually or suddenly, are changed by human impact or environmental change (Chapin *et al.* 2009). The transmission of the virus in the ecosystem acts in complex with the fixed agents, moving agents and external environmental factors. So we can neither directly find problems nor predict future changes (Re-quoted from Le *et al.*, 2008).

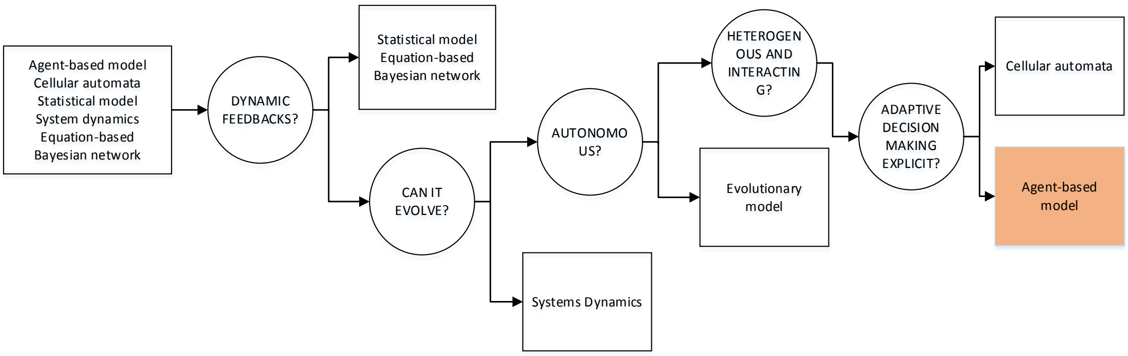


Figure 3. Analytical Tools of Complex System used in Decision Making (source adapted from Heckbert, Baynes, and Reeson 2010)

From figure 3, there are various models that are available for disease transmission. However, traditional epidemic models do not reflect the complex relationship in FMD transmission. In specific, such as statistical model or equation-based Bayesian network used formula from lots of empirical data and made a prediction, but it could only interpret formula based on empirical data (Parker *et al.* 2003). Therefore the dynamics and feedbacks between each agent cannot be performed, neither emergence nor evolution. System dynamics is a methodology and mathematical modelling technique for framing, understanding, and discussing complex issues and problems by formula structure where information and material flows and loops in the system (Parker *et al.* 2003). This model can explain changes of dynamics of various components by the use of feedback loops and stocks and flows (Wikipedia), but it only perform given formula and does not reflect the evolutionary phenomenon. A cellular automata can perform dynamics, evolutions, and feedbacks between components, but it has a lack of reflecting adaptive decision models of human environment (Kaimowitz and Angelsen 1998). Agent based model is introduced to overcome these limitations.

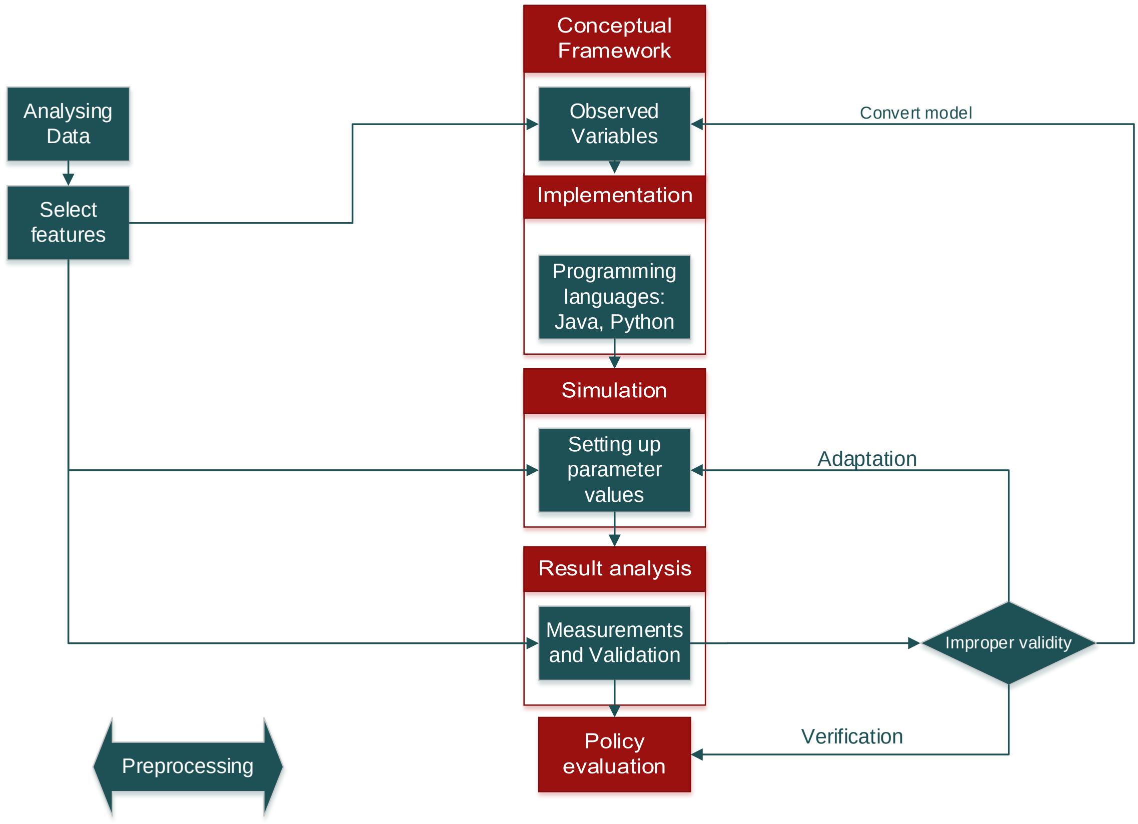


Figure 4. Procedure of Agent Based Model (source adapted from Yoon and Chae, 2005)

Agent based model is a bottom-up approach for simulating actions and interactions between agents in order to view their effects on the entire system (Yoon and Chae 2005, Yang and Hoegyung 2012). Agent based model produces macro-effects from micro-rules that construct a cornerstone of complexity methodological framework. Thus, within this model, dynamic phenomenon and evolution are emerged when there is a feedback between components. Also, interaction among autonomous agents and adaptive decision making for environmental change are also applied. Like this, the main advantage of this model is to develop a realistic movement model by putting simple assumptions of human resources and natural environment.

The simplest model of disease transmission model is an agent based SIR model. S-I-R is an abbreviation for 'Susceptible' (those individuals who are potentially capable of contracting the disease), 'Infected' (those individuals who are capable of spreading the disease), and 'Removed or Recovered' (those individuals who were infected are removed or recovered), and this is mostly used in disease diffusion modelling in complexity network system (Gatrell 2005, Curtis and Riva 2010). There are other epidemic models like SI (Susceptible-Infected), SEIR (Susceptible-Exposed-Infected-Removed), SIS (Susceptible-Infected- Susceptible) and SIRS (Susceptible-Infected-Removed- Susceptible), which are also based on the classification of the total population.

According to Lilliana and Suzana (2009), SEIR model is suitable for epidemiology modelling. SEIR model is important because it could diagnose symptoms of agents earlier. For instance, latency period is important to an individual because if the virus symptom is discovered in an 'exposed' period, the probability of recovery will increase. This model also has an advantage of discovering the spatial spread of FMD virus by computer simulation. It is expected that this model can present implications for national scale analyses based on local data.

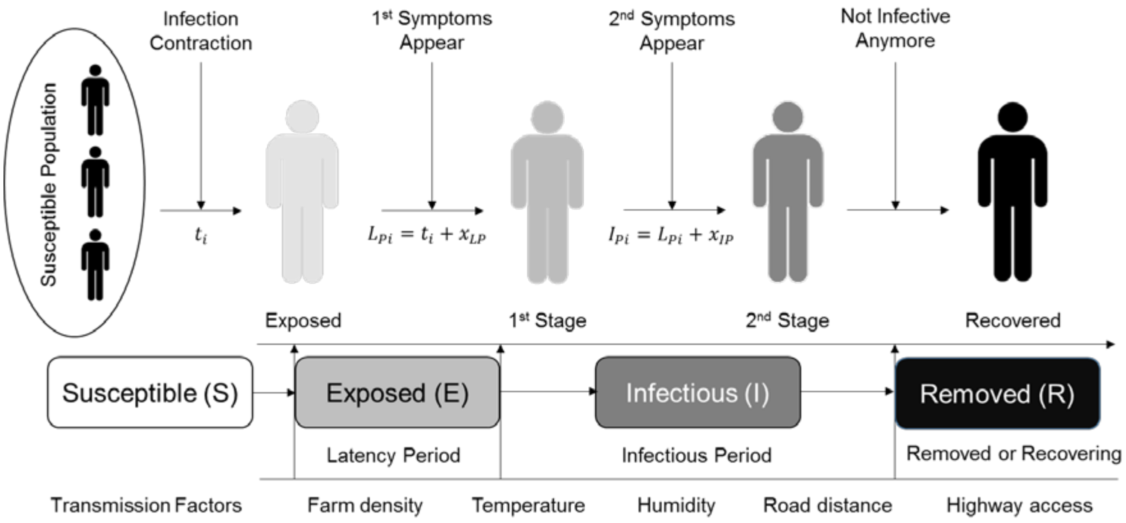


Figure 5. Progress of SEIR Infection Model (adapted from Lilliana and Suzana (2009))

The SEIR infection model consists of four periods. In susceptible status, animals are not infected but they have a possibility for transmission. Moving on, exposed or latency period is a time between an individual contacts a virus and the time when the virus is diagnosed as positive. After, infection period is the time before an infected individual gets recovered (Liliana and Suzana 2009).

In a meanwhile, there were studies that considered both complexity theory and landscape epidemiology (Lambin *et al.* 2010, Dion, VanSchalkwyk, and Lambin 2011, Dion and Lambin 2012). Lambin *et al.* (2010) got his idea from Pavlovsky (1966)'s work who identified the word 'landscape epidemiology', different from disease diffusion from spatial epidemiology, and carried on his vector-borne disease study. Lambin *et al.* (2010) pointed out that the factor of animal infectious disease represents pathogen dynamics, vector spatio-temporal dynamics, seasonal variability, human behaviour (low level of perception about infectious risk). Dion and Lambin (2011, 2012) used an agent based model to investigate how landscape heterogeneity influenced FMD diffusion in southern Africa. Agents were categorized into moving agents, which were buffalo and cattle, and fixed agents, which were land cover, livestock density and accessibility, vegetation, monthly mean temperature, and monthly mean precipitation. A total of 6 scenarios were designed as a combination of climate, hydrography, human habitat, vegetation, and fences. As a result, the number of contacts between cattle and buffalo mostly depended on the range of displacement of these animals, the number of fence breakages, and the increasing size of human habitat. This study is first to model spatial risk of FMD transmission combining social and natural changes into an integral system. Moreover, from a better understanding of these scenarios, we are able to improve spatial management of the disease control in natural areas. This study could be adapted to other areas, like South Korea, in changing few layers which suits that environment in specific.

2.4. Limitations in Previous Studies

Looking through previous studies, disease studies related to FMD (animal) disease have focused on virus itself or had not considered space. Veterinary approaches insist that FMD virus transmission is a movement of virus. The condition of FMD is composed of the virus' type, growing environment, virus sensitivity, and methods to diagnose and prevent it. Intriguingly, this study stresses that the FMD epidemic depends on animals because these animals have different virus types, latency period, and quantity of virus emission. Thus, scholars suggest if a FMD virus breaks out in a specific area, slaughtering, control of vehicle movement or vaccine injection must be enforced within adjacent regions according to infected animals, animals which have contacted infected animals, virus sensitivity of each animal. These studies are noteworthy for presenting causative viruses of FMD and discovered vaccines to cut off disease transmission, but they have restriction for designing transmission paths because its results only suggest solutions from molecular scale.

Disease ecology approaches argue that disease is a result of complex interactions (imbalance) between the triad of the agent, the host, and the environment. They interpret human as well as animal diseases (FMD, swine flu) with an epidemic triad. This simplified format makes it easy to understand animal disease in disease ecology. However, this field focuses on "agents (who?)", "behaviour (what?)", "conditions (how?)" but overlooks geographical space and transmission pattern which is really substantial in geography.

Previous studies of geographic diffusion also had limitations about disease transmission. In previous years, experience-based descriptive works were central in spatial diffusion theory, but this paradigm changed to computer-based works. Notwithstanding, these studies do not consider external environments. The theory itself only considers space and time, thus ignores environmental factors. In addition, mapping tools (e.g., ArcGIS, Geoda, ERDAS, and ENVI), statistical tools (e.g., SPSS, SAS, R) and methodologies do present disease distribution, or statistical results. However, these methods need data for analysis, but do not consider its uncertainty between agents and environments. To overcome these shortages, disease studies in geography must integrate space, time, and scale characteristics. Therefore, this study suggests an alternative method, which is the agent-based approach in order to simulate the reality of FMD transmission.

3. SPATIAL ANALYSIS OF FOOT-AND-MOUTH DISEASE

3.1. Introduction

Since 2000, FMD had occurred three times before the latest epidemic in November 2010: 15 cases in 2000, 16 cases in 2002, and 17 cases in January 2010. Until the latest epidemic, the government did successfully prevent FMD from becoming a nationwide epidemic (Kim 2011). However, the latest case occurred in 28th November 2010 at Andong city, which became the representative disaster at a national scale, spreading to 75 cities in 11 provinces throughout the whole country (see appendix 3).

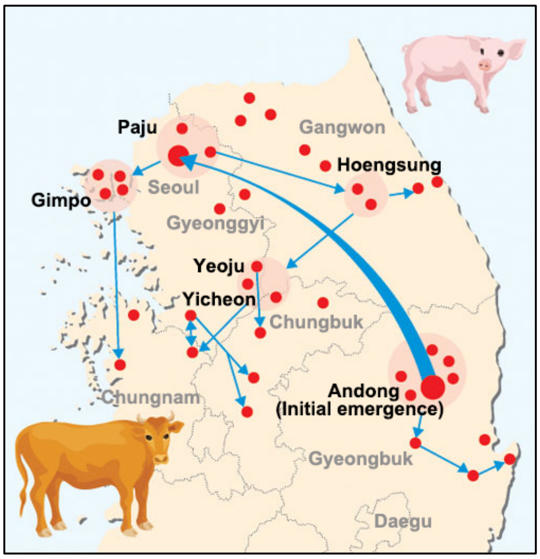


Figure 6. Spatial Diffusion of Foot-and-mouth disease (Source adapted from "Nongmin news 2011-1-28")

After FMD was eliminated, epidemic reports (QIA 2011, Yoo 2011) and spatial studies (Choi et al 2012, Park and Bae 2012) were published to the public. These results have provided information and insights on FMD transmission, such as FMD transmission conditions, symptoms, vaccinations, spread velocity, and cluster features. However, these studies had not examined spatial factors that affected the spread of FMD. Like disease ecologists, who are concerned about host's behaviour, their cultural and socio-economic context, and interaction with the environmental conditions, geographers should also find reasons in a geographical way.

The purpose of this chapter is to examine the spatial progress of FMD transmission and seek the factors which gave significant effects. Study period is from 28th November 2010 to 21st April 2011, which is 144 days in total. The datasets are composed of outbreak information, human environment, and natural environments. Datasets are exported from KOSIS, KOSTAT, and KAHIS. The following subchapters will first analyse the distribution of spatial progress of FMD transmission, then introduce spatial interpolation, slope calculation, and multiple ring buffer technique to find the relations of factors associated with FMD outbreak points.

3.2. Materials and methods

FMD outbreak data

Retrospective data on FMD outbreaks in South Korea are collected from Korea Animal Health Integrated System (KAHIS), provided by the Animal and Plant Quarantine Agency in South Korea. There are various diseases listed on the website which are categorised in types of first, second, and third class diseases. The variables of interest include: definitions, outbreak statistics, animal movement surveillance, GPS registry system for livestock vehicles, and other information about contagious diseases.

Nowadays, it is obligated to open the source of the legal animal contagious disease, in order to prevent additional outbreaks and transmission. The provided types of diseases are: FMD; swine fever; Aujesky's disease; Porcine Reproductive and Respiratory Syndrome (PRRS); *brucellosis*; *tuberculosis*; Highly Pathogenic Avian Influenza (HPAI); *Salmonella pullorum*; *Salmonella gallinarum*; Newcastle disease; mule deer chronic wasting disease. Data are updated consistently after the control agency clarifies reports of occurrence. All of the given data are shown on the website (table 1), but additional usage beyond the main purpose are prohibited. The disease is categorised into first class (red), second class (yellow), and third class (blue). Although the data are released in a livestock scale, these exclude individual livestock information, such as livestock names and location addresses.

Table 1. FMD Outbreak Output Example on KAHIS Website

Name of disease	FMD	Type of animal	Cow
Name of livestock	Park	Number of outbreak	30
Livestock address	Seoul	Diagnosis centre	ABC
Date of Outbreak	2013.1.1	End of disease	2013.1.8

Since this study focuses on FMD, FMD data between 2010.11.28 and 2011.04.21 were collected and reorganised from the FMD epidemiological report (QIA 2011).

Spatial datasets

Additional data sets for this study are constructed into two parts: human environments and natural environments. Human environments include highway accessibility and road proximity. Data are downloaded from Intelligent Transportation Systems Standard Node Link (nodelink.its.go.kr).

Natural environments include monthly-mean-climate (temperature, precipitation, humidity, wind direction, wind velocity) from November 2010 to April 2011, and topology (elevation) data. Hsu (2008) used monthly mean temperature to identify the weather impact on Japanese encephalitis. Muleme (2012) used seasonal mean temperature to find various disease outbreaks. Although Mikkelsen *et al.* (2003) argued that virus spread of FMD happened during low-wind condition, the research area has low altitude of mountains which have less relation to FMD spread. KAHIS shows FMD occurrence in temperature below zero and humidity over 60%. Thus, temperature and humidity are both considered in this study. These sets are derived from monthly reports of Korean Meteorological Administration (KMA) for climate data, which include 70 points. Elevation data is acquired from the National Spatial Information Clearinghouse (NSIC).

Methods

To display the outbreak points, the author use a geocoordination tool. This tool is provided by Biz-GIS (www.biz-gis.com). An ordinary kriging method in spatial interpolation is used to predict the values which are far from observatory points. Unlike other interpolation methods, kriging method states an error rate, and provides more accurate calculation than other interpolation methods (Diodato and Ceccarelli 2004). Slope is used in order to investigate geomorphological effect as natural barrier and is calculated with DEM (Digital Elevation Method) data. To analyse highway accessibility and road proximity, multiple ring buffer is used to calculate Euclidean distance from roads to outbreak points (Bessell *et al.* 2008). Bessell *et al.* (2008) describes the advantage of Euclidean distance in its work. All of the spatial analyses are performed in ArcGIS 10.1.

3.3. Results

Chapter 3 aims to examine the spatial factors that affect FMD. The initial result analyses the spatial path of FMD infection, and the subsequent result examines effects between various factors and outbreak data.

3.3.1. Spatial Process of FMD Transmission

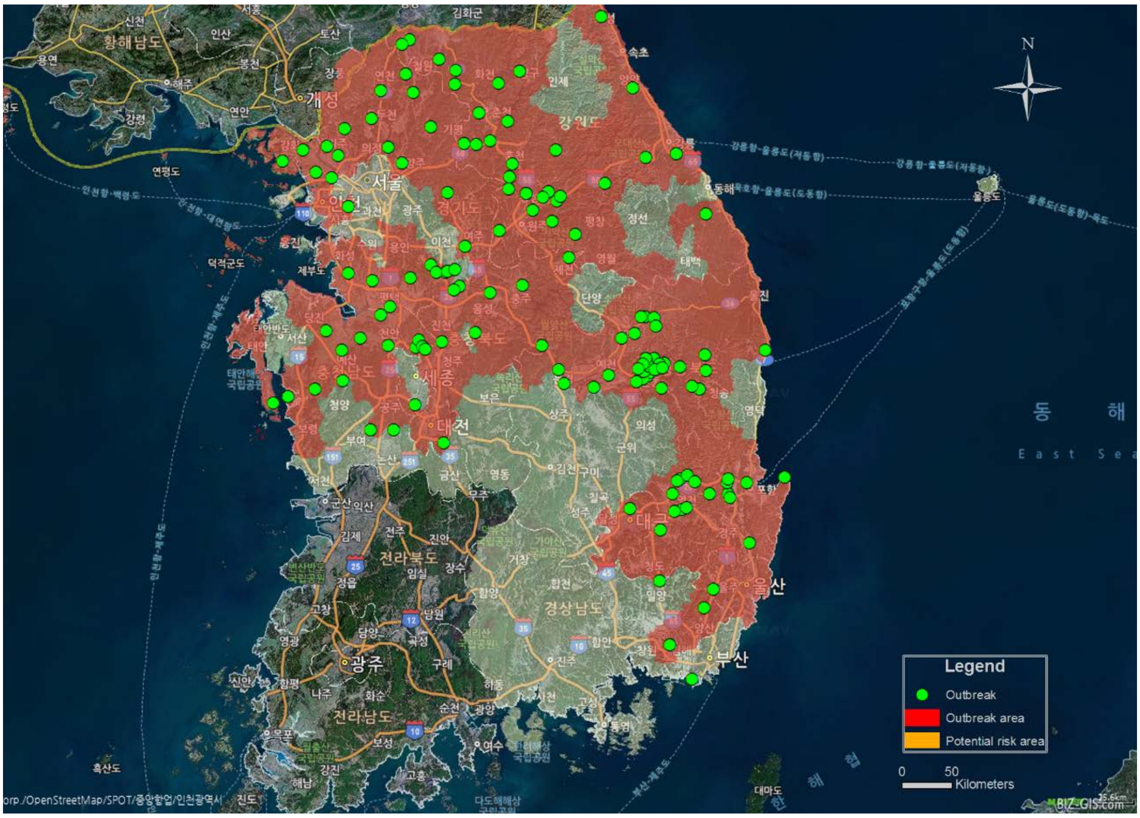


Figure 7. FMD Outbreak in South Korea (Web source adapted from Biz-GIS.com)

Figure 7 displays the spatial distribution of FMD. The green dot is an outbreak location derived from each livestock address, in which 153 cases occurred. Regions coloured red are cities which possess disease within its boundary. Orange regions depicts potential risk area of FMD. Cities which had at least one case is listed on the table below.

In table 2, 75 out of 230 cities (32.6%) are confirmed as a point for disease areas. The highest number of FMD outbreaks take place in Gyeonggyi (25%), followed by Gyeongbuk (21%), Gangwon (17%), Chungnam (13%), Chungbuk (10%), and so on.

Table 2. 2010-11 FMD Outbreak cities

Province	Total	City (si, gu, gun)
Busan	1	Saha-gu
Daegu	1	Dong-gu
Incheon	3	Ganghwa, Seo-gu, Gyeyang-gu
Daejeon	1	Dong-gu
Ulsan	1	Ulju-gun
Gyeonggyi	19	Anseong-si, Dongducheon-si, Eijungbu-si, Gapyeong-gun, Gimpo-si, Goyang-si, Gwangmyeong-si, Hwasung-si, Icheon-si, Namyangju-si, Pocheon-si, Pyeongtaek-si, Shiheung-si, Yangju-si, Yangpyeong-gun, Yeoju-gun, Yeonchun-gun, Yongin-si
Gangwon	13	Cheorwon-gun, Chuncheon-si, Daehwa-gun,Gangneung-si, Gosung-gun, Hoengsung-gun, Hongchun-gun, Hwachun-gun, Samcheok-si, Wonju-si, Yanggu-gun, Yangyang-gun,Yeongwol-gun
Chungbuk	8	Cheongju-si, Cheongwon-gun, Choongju-si, Eumseong-gun, Goesan-gun, Jecheon-si, Jeungpyeong-gun, Jincheon-gun
Chungnam	10	Asan-si, Boryung-si, Cheonan-si, Dangjin-si, Gongju-si, Hongsung-gun, Nonsan-si, Taean-gun, Yeongi-gun, Yesan-gun
Gyeongbuk	16	Andong-si, Bonghwa-gun, Cheongdo-gun, Chungsong-gun, Eiseong-gun, Gyeongju-si, Gyeongsan-si, Mungyeong-si, Pohang-si, Sangju-si, Uljin-gun, Yangyang-gun, Yecheon-gun, Yeongcheon-si, Yeongdeok-gun, Yeongju-si
Gyeongnam	2	Gimhae-sim, Yangsan-si

(Source adapted from KAHIS)

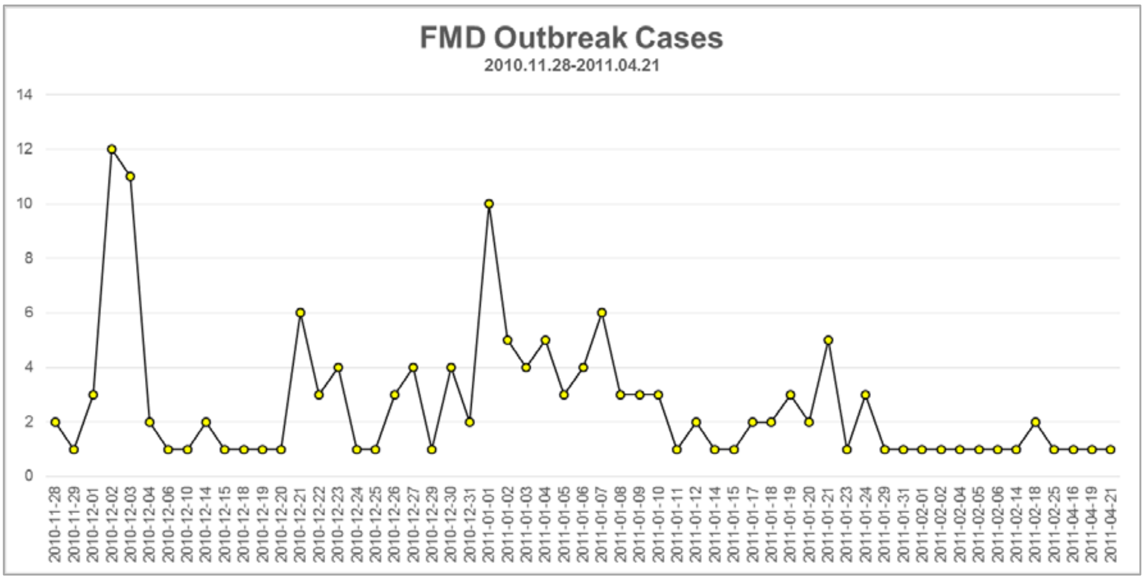


Figure 8. Cases of FMD Outbreak (data source from KAHIS)

During this outbreak, 153 (73.56%) out of 208 farms are verified as index points for disease transmission (Park *et al.* 2013). Each count is officially registered in KAHIS website. In figure 8, there are three massive outbreaks in the whole period: from 1st to 4th December 2010(17%), 21st to 23rd December 2010(8%), 1st to 7th January 2011(24%). This result supports previous studies that argued FMD disease disseminates in winter seasons (Hsu, Yen, and Chen 2008, Verma *et al.* 2008, Muleme 2012).

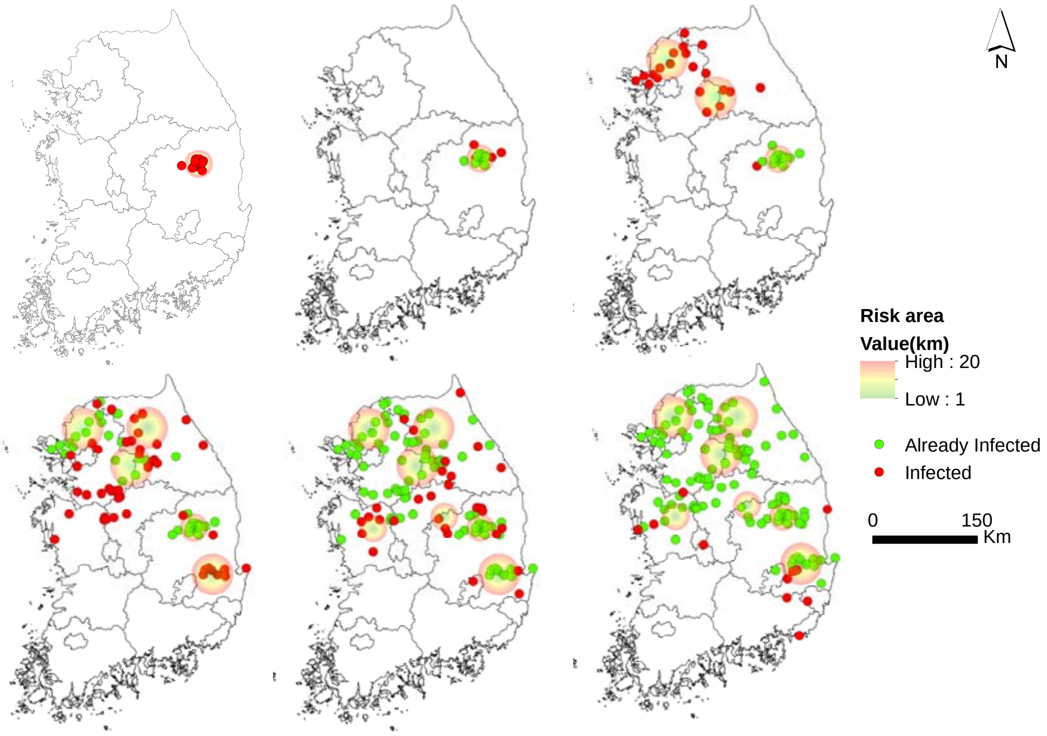


Figure 9. Spatial Process of FMD Transmission (source adapted from KAHIS)

To figure out spatial progress of FMD transmission, FMD outbreak data by date is shown in Figure 9. Livestock density is coloured in red. Previous report of Park *et al.* (2013) divided the FMD transmission progress into 6 periods: ① 2010.11.28-12.2, ② 2010.12.3-12.10, ③ 2010.12.11-12.26, ④ 2010.12.27-2011.1.7, ⑤ 2011.1.8-2011.1.20, and ⑥ 2011.1.21-4.21.

The initial period is determined from November 28th 2010 to December 2nd 2011. The initial strike occurred in Andong city (Andeok, Bukhu, Irwol, Nokjeon, Seohu, Waryong, Yeahn), far from livestock areas. Compared to large cities, Andong is a small traditional city (population of 150,000 persons) where there are less information on animal diseases. Due to lack of experiences, Andong city had no countermeasures for FMD (QIA 2011).

Because these livestock were far from highways or animal markets, it would have prevented epidemic if there were any early vaccine activities (e.g., drills, education).

Subsequent to the outbreak in Andong in November 2010, the FMD virus continued to cause outbreaks in north Gyeongbuk province from December 3rd to 10th, 2010. The QIA (2011) reported that the virus spread rapidly to the nearby cities, in which these cities are in one-day living zone (Andong to Youngju, Yechon, and Youngyang). Also, it is revealed that most of the cattle livestock in Andong used same animal feeds. As a result, vehicles moving animal feeds carried virus from infectious livestock to susceptible livestock.

Third period started from 11th December to 26th December 2010, leaping to Gyeonggyi province. The disease occurred in Paju and Yeoncheon which is far-distant (approximately 250km) from the early infected regions. The Machinery for processing livestock soil was delivered from Andong to Paju in 17th November, and this facilities transmitted virus after delivering dried soil products to close livestock. This result is estimated from facilities which were located in 200-500m distance of infected livestock. Livestock in Gyeonggyi province were breeding cattle and pigs in a large-scale farm, similar to Andong. Moreover, it is estimated that virus spread to adjacent cities since most of the livestock used the same road (National road number 3). With the highest amount of human and material mobility, it appeared that livestock in Gyeongyi region were already infected before the virus was verified.

Fourth period started from 27th December 2010 to 7th January 2010, revealing as an epidemic phase. After northern and eastern Gyeonggyi province (Yeoju and Yangpyeong), southeastern area of Gyeongbuk province (Gyeongju and Pohang) was infected, this virus made a new leap to Hoengsung and Hongchun in Gangwon province. Hoengsung, located in the centre of Gangwon province, is a core for livestock products. Thus, products delivered from Hoengsung were the key components in spread in Gangwon province. After vehicles were recognized as the key factor of FMD transmission, control measures taken by the Korean government to stop infection in which virus was detected markedly.

From 8th January to 20th January 2011, the virus was able to spread and infect through the whole country. All the infected animals were located not only in Gwanwon province but also in Choongchung province (Boryong, Chungju, Dangjin, Goesan, Jincheon, and Umseong) and southern Gyeonggyi province. Actually, the two close provinces share farming resources such as feeding vehicles, and shipping vehicles, thus means that the virus is transmitted by human or vehicles. Although controlling measures were acted for FMD elimination, this job was performed poorly in these areas due to the cold weather.

The final period was determined from 21st January to 21st April, until the FMD epidemic was officially stopped. The emergency vaccination continued from December 2010 for all livestock in 10km radius from infected farms and on city junctions and highway interchanges (QIA 2011). There were still intermittent virus in some cities, but it eventually ended in April.

3.3.2. Spatial Factors Causing FMD Transmission

Table 3 describes winter mean temperature during the FMD period. The Korean Meteorological Administration (KMA) determines winter period between December and February. The average temperature of cities (except Jeolla and Jeju) show that almost 25% cities are over 0°C, 73.6% are between -5°C and 0°C, and 1.6% are under -5°C. Here, we see over 75% of cities are below 0°C which maintain cold weather. Like previous studies have argued, FMD virus is more common during the winter season (QIA 2011, Yoo 2011, Park *et al.* 2013).

Table 3. Winter Mean Temperature in 2010-11 Korea

Temperature	Cases	%
Over 0°C	32	24.8
-5°C < x < 0°C	95	73.6
Under -5°C	2	1.6
Total	129	100

Using kriging method, examples of temperature and humidity in Andong and Seoul are displayed in Figure 10 and Figure 11. Despite the long geographical distance between Andong and Seoul, which is approximately 200km Euclidean distance, both cities have a small difference in temperature and humidity. Mapping results of spatial interpolation are illustrated in appendix 4 and 5.

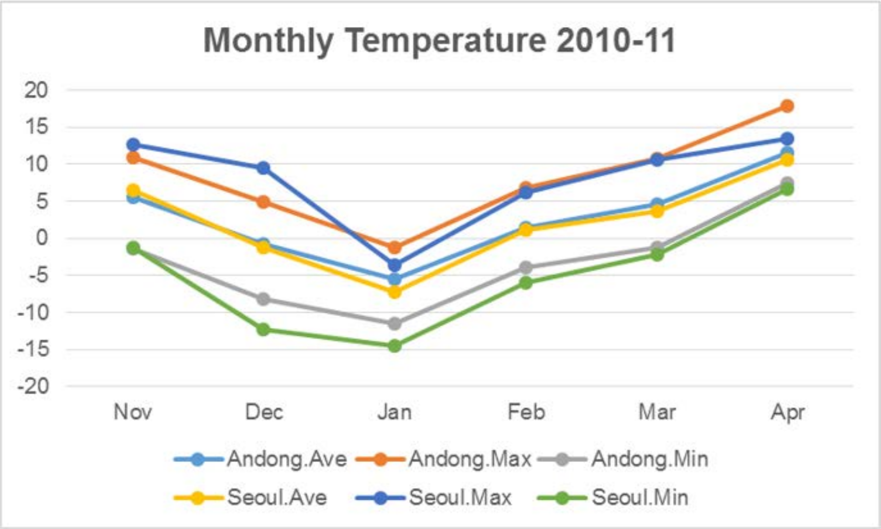


Figure 10. Monthly Temperature in Andong and Seoul 2010-11
(source adapted from KMA)

Temperature variation is another significant data for FMD occurrence (Yoo 2011). Figure 10 and table 4 illustrates some decrease from November to January (Nov-Dec: Andong -6.2℃, Seoul -7.8℃; Dec-Jan: Andong: -6.2℃, Seoul: -5.9℃), and an increase from February to April (Jan-Feb: Andong +6.9℃, Seoul +8.4℃; Feb-Mar: Andong +3.2℃, Seoul +2.4℃; Mar-Apr; Andong +6.9℃, Seoul +7.1℃). From this result, a wide temperature variation can easily infect virus to weak immunity.

Table 4. Climate Variation in Korea 2010-11 Winter season (129 cities)

Factors	Dec-Nov	Jan-Dec	Feb-Jan	Mar-Feb	Apr-Mar
Temperature	-6.17°C	-5.58°C	6.86°C	2.77°C	6.60°C
Humidity	1.3%	-5.4%	7.3%	-11.8%	6.5%

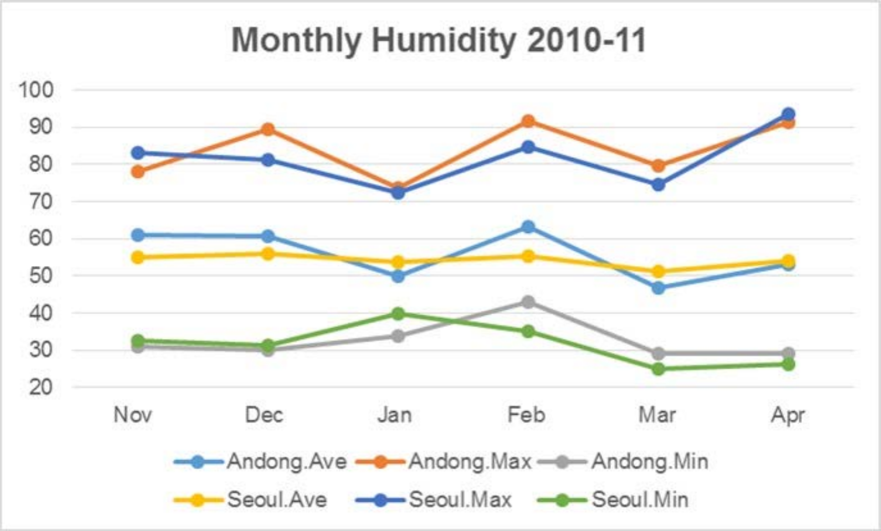


Figure 11. Monthly Humidity in Andong and Seoul 2010-11 (source adapted from KMA)

Compared to temperature values, monthly humidity values do not show a remarkable difference in the study period. Due to less precipitation in winter seasons, the values are observed at constant. Yoo (2011) and The Korea Pork Producers Association insists that the FMD virus can remain its viral features when the relative humidity is over 60% but it rapidly extinct below 50%. Table 4 shows that 58.9% of cities satisfy this condition.

Table 5. Winter Mean Humidity in 2010-11 Korea

Humidity	Cases	%
Over 60%	76	58.9
Under 60%	53	41.1
Total	129	100

Slope data are computed with slope calculator function (Figure 12). Slope is selected as a form of barriers which interrupt animal and human movements across them. The author assumes that low land areas will have a higher probability to have FMD than high lands. Results from slope calculator illustrate that the outbreak location is observed in lowlands: 90 cases in 0 - 5°, 34 cases in 5 - 10°, 14 cases in 10 - 15°, 11 cases in 15 – 20°, and 4 cases were over 20°. The result notifies that most of the outbreak points (81%) occur at low altitude farms. Thus it is understood that slope is highly relevant to FMD transmission.

Table 6. Classification Table of Slope

Degree of slope (°)	Cases	%	Statistics
0 – 5	90	58.8	Min: 0 Max: 34.1 Mean: 5.95 Stn.d: 4.59
5 – 10	34	22.2	
10 – 15	14	9.2	
15 – 20	10	7.2	
20 -	4	2.6	
Total	153	100	

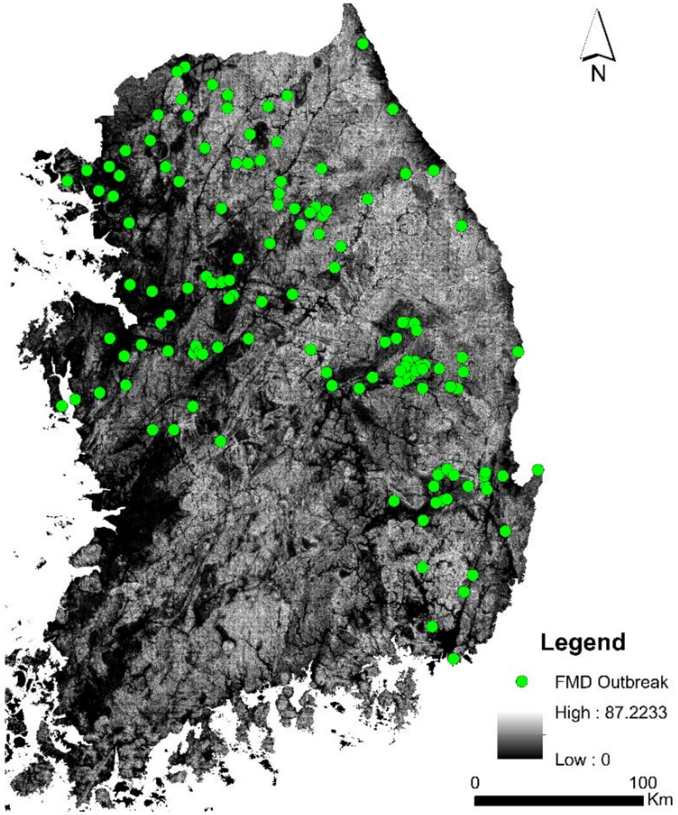


Figure 12. Slope and FMD Outbreak Data

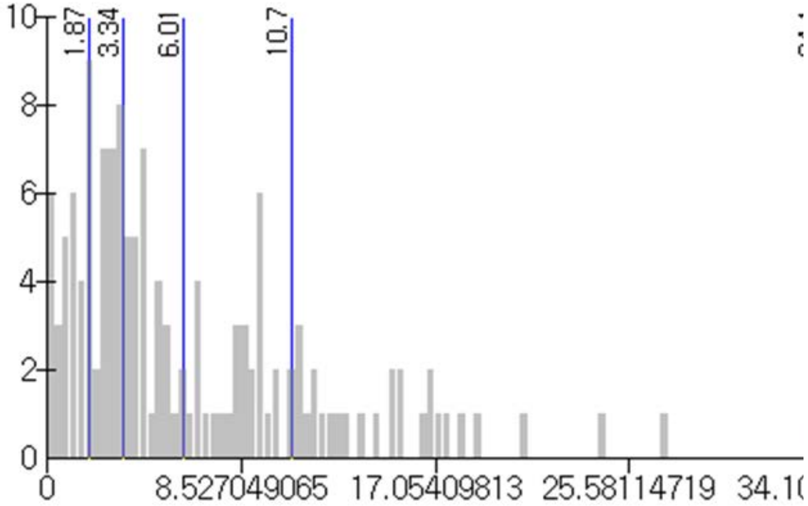


Figure 13. Slope Classification Statistics

On the contrary, variables associated with roads increase FMD transmission by accelerating the pathway for humans and animals. Over 77% of the outbreak points are located within 5km of national road and 74% of the outbreak points are connected to the highway interchange in 10 minutes (if a person drives 60 km/h). From the results, it is found that road distance and road network give a considerable effect to FMD transmission. Bessel *et al.* (2008) notes that highway did not act as a barrier but act as a *permeable indicator set*.

Table 7. Distance from Roads and FMD Outbreak Points

Road	Cases	%	Highway	Cases	%
Within 5km	118	77.1	Within 5km	42	27.5
Over 5km	35	22.9	5km – 10km	70	45.8
			Over 10km	41	26.8
Total	153	100	Total	153	100

(sources adapted from ITC)

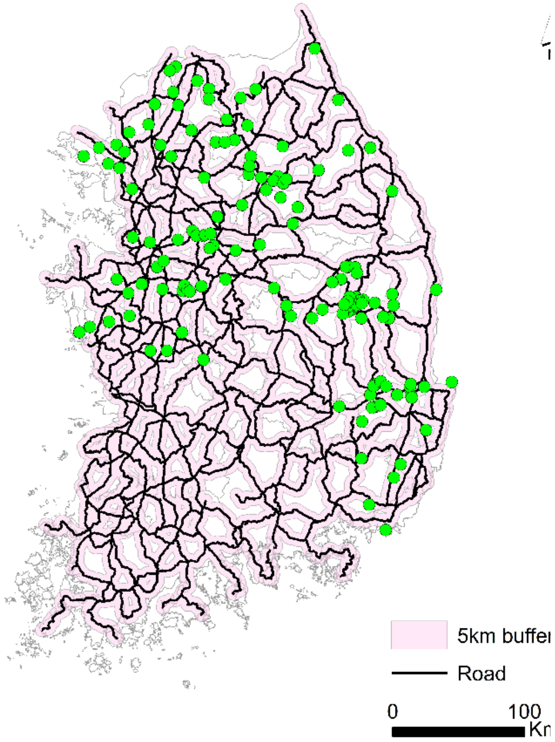


Figure 14. Road Proximity

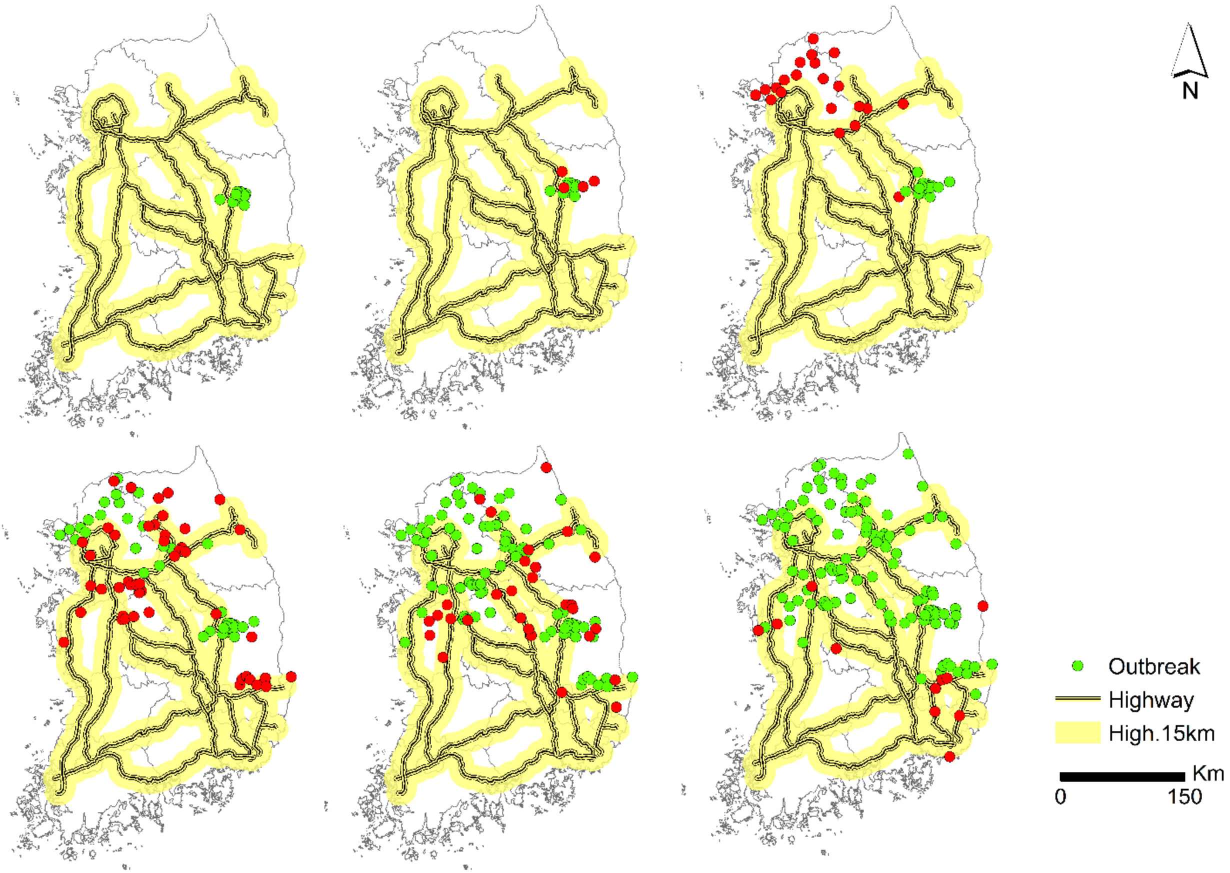


Figure 15. Highway Accessibility

3.4. Summary

The FMD epidemic in South Korea has been the subject of continuous epidemiological analysis to understand possible factors that affected disease transmission. In the first section of the research disease transmission is analysed with outbreak data, temperature, humidity, highway, and general road.

This chapter is based on 153 outbreak points located in Gyeongbuk, Gyeongnam, Daegu, Chungbuk, Chungnam, Gangwon, Gyeonggyi. As depicted in 3.3.1, FMD virus initially occurred in Andong city in 28th November 2010, and spread to Gyeongbuk province within a couple of weeks (QIA 2011). The national-scale epidemic is verified after the machinery was moved to Gyeonggyi (Paju, Yeoncheon), where large multiple livestock were located. The virus subsequently moved to Gangwon, southern Gyeonggyi, and finally to Choongchung province. As a matter of fact, this infection geographically spread throughout the whole country, where it initially occurred in the southeastern region, moved to the northwest, travelled to the eastern region, came back south, and finally eliminated near Andong. During FMD transmission, 32% of cities are diagnosed as infected areas, in which Gyeonggyi (25%), Gyeongbuk (21%), and Gangwon (17%), Chungnam (13%), and Chungbuk (10%) are highly infected. In figure 8, three massive outbreaks are found during FMD period. The first was from 1st to 4th December 2010 (17%), the second was from 21st to 23rd December 2010 (8%), and the last was from 1st to 7th January 2011 (24%). This results show the direction of FMD spread, risk areas and the massive outbreak period which are the basic information for this study.

From spatial analysis, it is known that temperatures during winter season give effect to a premise of FMD outbreak. Depicted in figure 10 and figure 11, a large temperature variation during winter weakens animal immunity and leads to easier infections. This supports previous studies that describe either monthly mean temperature or seasonal mean temperature can affect disease transmission (Hsu, Yen, and Chen 2008, QIA 2011, Muleme 2012).

However, humidity does not show a substantive difference. Monthly humidity gap between November and December is 1.3%, between December and January 5.4%, between January and February 7.3%, February and March 11.8%, March and April 6.5%. Compared to temperatures, humidity does not show a substantive difference, but we see that 60% of the cities satisfy the condition in 2010-11. This supports previous studies that insist high humidity conditions favour to affect FMD because when its percentage is high, it likely carries virus to different places via air (Donaldson 1972, Donaldson, Lowe, and Ward 2002, Alexandersen *et al.* 2003).

In figure 12, FMD outbreak points are located in low degree areas. As a result, 60% of the outbreak points occurred between 0 – 5°. From previous studies, Muleme (2012) insists that farms with a location in low lands have a good probability of having influenza transmission. Mikkelsen *et al.* (2003) equally indicate that virus transmission happens in low-level mountain and constant wind.

Results from figure 15 and figure 16 find out that over 77% of outbreak points are close to general roads and 74% were adjacent to highway entrance. This outcome supports previous study of Choi *et al.* (2013) that argued road accessibility and connectivity could accelerate FMD transmission. Other studies insisted that dynamic mobility of farmers, tourists, and habitats can increase disease via person or via road metrics (Angulo *et al.* 1985, Kao *et al.* 2007, Convery *et al.* 2008).

Intriguingly, there are still lots of factors that cause FMD outbreak and transmission. Alexanderson *et al.* (2003), Wilesmith *et al.* (2003), and Green, Kiss and Kao (2006) argue that FMD is an airborne disease in which virus is influenced from agent to agent through air. However, the QIA (2011) already announced that there are no virus collected in 30 air samples in Yicheon city. In addition, there are no data for traffic statistics associated with animal movement. KAHIS announced that the animal transports must stick GPS tags on trucks in order to track one's movement. This strategy was tested in a pilot program in 2013 on 500 trucks, and it will expand to all trucks from 2014.

To sum, this chapter analyse spatial factors that influenced FMD epidemic in South Korea 2010-11. This study choose the primary risk factors that are listed as temperature, humidity, slope, highway accessibility, and road proximity. There are numerous factors that affected FMD, but the author choose aforementioned factors to focus on their effects. Actually, all of the chosen factors are directly and indirectly match the Veterinary epidemiological report (QIA, 2011), which is mentioned in chapter 1.

4. IDENTIFICATION OF RISK FACTORS ASSOCIATED WITH FOOT-AND-MOUTH DISEASE

4.1. Introduction

FMD is a highly infectious disease of cloven-hoofed animals. FMD outbreak that occurred in Andong city had spread to the whole country except for Jeolla and Jeju (figure 7). This disease infected 75 cities and killed almost 3.5 million animals (figure 8).

The QIA (2011) reported some reasons of nationwide spread which was listed as high livestock density in an area, good road linkages and low temperature. Park *et al.* (2013) supported this report, notifying that FMD transmission was derived mainly from pig-farm complexes that contained large amount of virus, and short distance between farms. As a veterinarian, Yoo (2011) indicated external environments can influence FMD transmission (e.g., temperature, humidity, hay, and wild animals). Bessell *et al.*(2008), Mingora *et al.* (2013), and Muleme (2013) support infectious diseases that are mainly affected by road proximity and linkage.

To prevent FMD disease in the future, it is necessary to understand risk factors that are relevant to FMD transmission. Therefore this chapter aims to investigate risk factors that affect the spatial spread of the FMD epidemic. Case and control method are used for this study to elucidate the statistical difference between case and control cities.

4.2. Materials and Methods

Dataset

In this study, a case and control study is conducted in order to elucidate cause and effect among these factors. 'Case cities' are selected from positive cities, which had infected animals within livestock, whereas 'control cities' were from negative cities, which had no infected animal until the epidemic had ended. This data is aggregated into scaled 83 administrative units (Si, Gun, Gu) within eleven provinces where FMD mainly occurred.

Datasets from chapter 3 are adapted to this chapter, which are temperature, humidity, slope, highway accessibility, and road proximity. Since this chapter use case and control method, the author categorise these data by city level. On account of statistical features, whereas variables have one value in one row, the author input seasonal mean temperature and humidity in the analysis.

Livestock ratio is chosen as a variable. As QIA (2011) and Park *et al.* (2013) indicated, high livestock density and short distance between farms are significant risk factors that affected 2010-11 FMD. Livestock data are provided at KOSIS which is categorised by cities (si, gun, gu). In order to gain density values, livestock data are divided by cultivated area, because most livestock sites are affiliated to these areas (KOSTAT 2009, Oh 2011).

In consequence, 7 variables are composed of risk factors that are relevant to city (livestock) transmission: 1) FMD outbreak, 2) highway accessibility, 3) road distance, 4) livestock density, 5) temperature, 6) humidity, and 7) slope. These variables can be formalised into:

Logit (Prevalence [1]) = Transmission [2, 3] + Vulnerability [4] + Environment [5, 6, 7]

Table 8. Explanations of the Variables used in Case-control Study

	Variables	Type	Description
Dependent Variable	FMD outbreak	Dichotomous	If outbreak = 1, otherwise 0
Climate	Temperature	Continuous	°C
	Humidity	Continuous	Relative humidity (%)
Density	Livestock density	Continuous	Livestock no. / Livestock area
Topology	Slope	Continuous	Degree (°)
Transport	Highway accessibility	Dichotomous	If adjacent = 1, otherwise 0
	Distance to nearest main road	Ordinal	1km = 3, 2km= 2, 3km >=1

Methods

To solve the cause-and-effect relationship between FMD outbreak and reveal risk factors, logistic regression is best used as an analysis method (Muroga *et al.* 2013). Logistic regression is regularly used rather than linear regression, since many interesting variables in disease studies have dichotomous data: for instance, being sick or not, passing or fail an exam, or earning high or low income can influence whether an employee may be promoted or not (Burns and Burns 2008). In this study, outbreaks per city will be classified as 1 (positive) or 0 (negative).

According to Burns and Burns (2008), there are two main uses of logistic regression. The first is to predict group membership. Since logistic regression calculates the probability of positives over negatives, the analysis is resulted in an odds ratio format. Moreover, logistic regression discovers relationships and strengths among the variables.

In this study, assumptions of logistic regression notes as follows:

- Logistic regression does not assume a linear relationship between the dependent and independent variables.
- The dependent variable must be a dichotomy (2 categories).
- The independent variables does not need to be interval, nor normally distributed, nor linearly related, nor of equal variance within each group.
- The categories (groups) must be mutually exclusive and exhaustive; a case can only be in one group and every case must be a member of one of the groups.
- Larger samples are rather needed than for linear regression because maximum likelihood coefficients are large sample estimates. A minimum of 50 cases per predictor is recommended.

Explanation of logistic regression equation is shown as below.

$$\text{logit}[p(x)] = log\left[\frac{p(x)}{1-p(x)}\right] = \alpha + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_i x_i \text{ (Equation 1)}$$

$$\mathrm{p} = \frac{\exp^{(\alpha+\beta_1 x_1+\beta_2 x_2+\cdots+\beta_i x_i)}}{1+\exp^{(\alpha+\beta_1 x_1+\beta_2 x_2+\cdots+\beta_i x_i)}} \text{ (Equation 2)}$$

α = the constant of the equation

β = the coefficient of the predictor variables $\mathrm{X_i}$ for i= 1, 2, …, n.

p = the probability that a case is in a particular category

exp = the base of natural logarithms (approximately 2.72)

Here, *logit* (p) is the log of the *odds* that the dependant variable is 1. P can only range from 0 to 1 since probabilities must be between 0 and 1, whereas logit(p) scale ranges from negative to positive infinity (Gelman 2007, Burns and Burns 2008). The natural logarithm (base *e*) is used normally. Equation 2 looks like a linear regression but the principles they used is maximum likelihood, which maximizes the probability of getting the observed results given the fitted regression coefficients. For instance, in a case of logit (0.5) = 0 and logit (0.6) = 0.4, adding 0.4 on the logit scale corresponds to a change from 50% to 60% on the probability scale (Gelman 2007).

$$\text{Odds ratio}(\theta)= \frac{odds_1}{odds_2} = \frac{\theta_1/(1-\theta_1)}{\theta_2/(1-\theta_2)} = \frac{\theta_1\times(1-\theta_2)}{\theta_2\times(1-\theta_1)} \quad \text{(Equation 3)}$$

$$\text{Log}(\theta) = \log\frac{\frac{p_1}{1-p_1}}{\frac{p_2}{1-p_2}} = \log\left(\frac{p_1}{1-p_1}\right) - \log(\left(\frac{p_2}{1-p_2}\right) = \text{logit}(p_1) - \text{logit}(p_2) \quad \text{(Equation 4)}$$

As P is a probability from 0 to 1, p/(1-p) is a corresponding odds. In a similar way, odds ratio (θ), short as OR, is a probability of two different, related probabilities that does or does not have a quality. OR is computed in two steps: 1) compute odd_1 and odd_2, 2) divide odd_1 to odd_2 to get an OR result. If an odds ratio is 1, then the event is equally likely in both groups; if an odds ratio is over 1, then the event is more likely in group 1; and if an odds ratio is below 1, then the event is more likely in group 2. R package version 3.0.1. is used in this study, and Wald statistics checks goodness-of-fit.

4.3. Results

To assess the results of case and control study of 2010 FMD epidemic, basic information for case and control is descripted in table 9.

Table 9 Synthesis of Case and Control cities

Variables	Case			Control		
Count	53			31		
	Min	Mean	Max	Min	Mean	Max
Temperature	-6.33	-2.29	2.5	-3.73	1.632	1.23
Humidity	44	59.9	67	47	60.8	69
Slope	3.62	12.12	20.51	3.28	10.99	21.24
Highway	0	0.717	1	0	0.774	1
Road prox.	1	1.79	3	1	2.19	3

There are 53 case cities and 31 control cities in this study. All of the cities are located in the potential risk area (see figure 7). The association of temperatures has a difference between case and control cities, which mean values are -2.29°C and 1.632°C. On the contrary, humidity, which values are 59.9% and 60.8%, did not seem a big difference. Slope has a 1.13 degree difference between two conditions. Likewise, highway and road proximity show a similar mean value between the two conditions. Hence, except temperature, the rest of the variables indicate that case and control cities have similar environment, implying this condition is suitable for analysis.

Table 10. Classification Table

Observed		Predicted		
		Outbreak		Accuracy (%)
		0	1	
Outbreak	0	24	7	77.4
	1	9	44	83.0
Overall percent				81.0

On the classification matrix, "observed" means outbreak values, which are either negative or positive. Predicted values in logistic regression mean 0 for negative, and 1 for positive. As a result, whereas 24 out of 31 (77.4%) control cities predicted correct, 44 out of 53 (83.0%) case cities predicted right. To sum, this analysis is implemented in 81 percent of correction.

Table 11. Logistic Regression of FMD Affected Factors

Variables	Coefficient	Std.Error	Wald	Sig.	OR	95% C.I. for Odds	
						Lower	Upper
Temp*	0.7614	0.2625	2.790	.0037	0.47	0.26	0.75
Humidity	0.1391	0.0833	3.929	.0948	0.87	0.73	1.01
Slope	-0.194	0.0979	3.929	.0475	0.82	0.67	0.99
Farm den*	0.321	0.0934	11.806	.0006	1.38	1.17	1.69
High acc*	0.3002	0.6843	0.192	.6609	1.35	0.35	5.36
Road dist*	-0.803	0.3698	4.716	.0299	0.45	0.21	0.90
Constant	8.30	5.67	2.141	.1433			

OR*: Odds Ratio, Temp*: Temperature, Farm den*: Livestock density, High acc*: Highway accessibility, Road dist*: distance to road

The results of multivariable analyses are shown in table 10. A total of six variables are selected for the analysis: 'temperature', 'humidity', 'slope', 'livestock density', 'highway accessibility', and 'road distance'. The odds ratio of case farms having the factor 'livestock density' (1.38 times), 'highway accessibility' (1.35 times), were significantly higher than control livestock's, while 'temperature' (0.47 times), 'humidity' (0.87 times), 'slope' (0.82 times), 'road distance' (0.45 times) resulted in opposite.

$$\boldsymbol{log\widehat{Y} = -0.7614 * temp - 0.1391 * humidity - 0.194 * slope + 0.321 * farmden + 0.3 * highacc - 0.803 * roaddist + 8.30}$$

To identify the strength between each variables, Wald statistics are provided for examination. Variables are ranked: 1) livestock density, 2) road distance, 3) slope, 4) humidity, 5) temperature, 6) highway accessibility in order. However, only 1, 2, 3, and 5 are statistically significant in this model.

Table 12. Model Summary

Step	-2 Log likelihood	AIC	Chi-square
1	74.999	89	18.1, df=6, p < 0.006

Number of Fisher Scoring iterations: 6

Finally, for the validation of this model, -2LL, AIC, and chi-square is provided for the overall significance. All three tools are good for validation, observing the actual data that accurately fit the model. Normally, *goodness-of-fit* in each models are proved when -2LL value is high or AIC value is low. While chi-square method, analysed by two hypothesis, has 6 degrees of freedom, a value of 18.1 and a probability of p < 0.006 [Table 7]. Hence, it is insisted that the model has a goodness-of-fit, indicating that the variables do have significant effect to the predictors.

4.4. Summary

The aim of chapter 4 is to investigate cause-and-effect relationship that transmitted FMD between countries during the epidemic in 2010-11 using case-control model. 84 cities are selected for this study, among these, there are 51 case cities and 33 control cities. Six variables are considered as risk factors associated with transmission of FMD.

As a result, livestock density, road distance, highway accessibility, slope, temperature, and humidity are indicated as risk factors associated with FMD transmission. Variables as road distance and highway accessibility are interpreted in diffusion factor; livestock density is interpreted in vulnerability factor; slope, temperature, and humidity are interpreted in environment factor. The odds ratio of case farms having the factor livestock density (1.38 times) and highway accessibility (1.35 times), is significantly higher than control livestock's, whereas temperature (0.47 times), humidity (0.87 times), slope (0.82 times), and road distance (0.45 times) result in opposite. To identify the strength between each variables, Wald statistics are provided for examination. Variables are ranked: 1) livestock density, 2) road distance, 3) slope 4) humidity, 5) temperature, 6) highway accessibility in order. Although humidity and highway accessibility have no impact on the risk of FMD transmission, livestock density, road distance, slope, and temperature are statistically significant in this model. Overall model has a good fit showing 74.99 in -2loglikelihood, 89 AIC, 18.1 chi-square points, and $p < 0.0006$ value.

For diffusion factor, it is noticed that movements of people and vehicles are important ways for FMD virus transmission (Grenfell and Dobson 1995, QIA 2011, Muleme 2012, Park and Bae 2012, Carrel and Emch 2013, Gaudart *et al.* 2013). Although there were restrictions for vehicle mobility, it could not stop FMD from transmission. Thus, FMD transmission could have been effectively controlled if the vehicles from other regions are restricted or the prevention tool have been constructed near livestock or highway interchanges.

For vulnerability factor, the livestock density is statistically associated with FMD transmission. As mentioned on the 2011 FMD epidemiologic report, this high probability of livestock density results from topological restrictions of grazing.

Finally, for environmental factor, 'slope' and 'temperature' are statistically associated with FMD transmission, while 'humidity' could have made sense but is not statistically significant. Various studies (Kitron 1998, Mikkelsen *et al.* 2003, Brown, McLafferty, and Moon 2009, Lambin *et al.* 2010, Dion, VanSchalkwyk, and Lambin 2011) insist that FMD is an airborne disease, but its virus' components are restricted by mountain barriers. An epidemiological investigation team collected the 68 samples of the air and only two samples were detected positive with FMD virus. So far, there are hardly any cases of airborne disease in this epidemic. Meanwhile, FMD virus occurs and easily transmits when temperature decreases and relative humidity is over 60% (Yoo 2011). However, careful interpretation is required because temperature is not the representative factor for FMD spread. Early studies (Verma et al. 2008, Dion and Lambin 2012) stressed that FMD outbreaks in India and South Africa were discovered as a high humidity and rainy condition. Although there might have Humidity and precipitation influence in Korea, this study found no significant fit from the result, meaning no relevance with Korean FMD epidemic.

5. AGENT BASED APPROACH TO DISCOVER POTENTIAL FACTORS OF FOOT-AND-MOUTH DISEASE

5.1. Introduction

Epidemic disease takes place through spatial interactions between agents (Del Valle, Mniszewski, and Hyman 2013). Also, emerging diseases like FMD are influenced by host's behaviour and external environments (Meade and Emch 2010, Carrel and Emch 2013). Previous studies thus indicates that 2010-11 FMD epidemic as well spread through agent-to-agent contact.

Recent studies reflect this idea to mathematical models. In the literature review, there are several approaches related to disease transmission including spatial statistical models (Choi et al 2012, Park and Bae 2012), network models (Buchanan 2003, Ortiz-Pelaez et al. 2006, Choi et al 2012), and agent-based models (Liliana and Suzana 2009, Dion and Lambin 2012, Del Valle, Mniszewski, and Hyman 2013). These models gave a good insight on disease transmission issues such as betweenness, connectivity, centrality, spatio-temporal process, and uncertainty. Yet, only agent-based models can capture this stochastic contact process between agents and external environments, and consider temporal issues in the model.

Here, this chapter aims to identify the impact of determinant factors that influence FMD transmission speed based on agent based model. The motive of this chapter is to analyse how much the effect of determinant factors from statistics models is in the agent based model. The structure of this chapter is as follows: First, materials and method show agents, flowchart model, simulation toolkit and assumption. This model will display changes of infection period per simulation. In the model, viruses are transmitted while agents move and interact with others. Agents have latency period before they are infected. Animals as well as vehicles transmission is considered.

5.2. Materials and methods

5.2.1. Agents

Related to disease transmission, we must focus on individual parameters as well as understand processes within the whole structure. Based on complexity theory, agents deteriorate disease while they interact and self-organize themselves in the geographical space. Agents are largely divided into active agents and fixed agents. In this study, active agents are cattle, pigs, and trucks, while fixed agents are road and vaccine patch.

5.2.2. Assumptions

To construct agent-based model, some assumptions are descripted as follows:

- Agents' birth and elimination is not considered (S+E+I+R = N = constant).
- Each animal has the same infection rate.
- Infection rate is 60% (Eblé *et al.* 2006).

- Agents within livestock move in random space, while trucks only move on roads.
- Infected animals can transmit virus to vehicles.
- FMD virus has a latency period from 2 to 14 days (140 ticks in model).
- Livestock can be chosen, from 1 to 30. An infected animal exists on the chosen livestock.
- There are six vaccine patches. If this operates, it has 50 percent probability of treatment (KAHIS 2013).
- To control highway effect, select either “highway” or “road” for speed change.
- Emergence of a new virus is determined to 30% in overall population after initial outbreak (Del Valle, Mniszewski, and Hyman 2013).

5.2.3. Model Flowchart

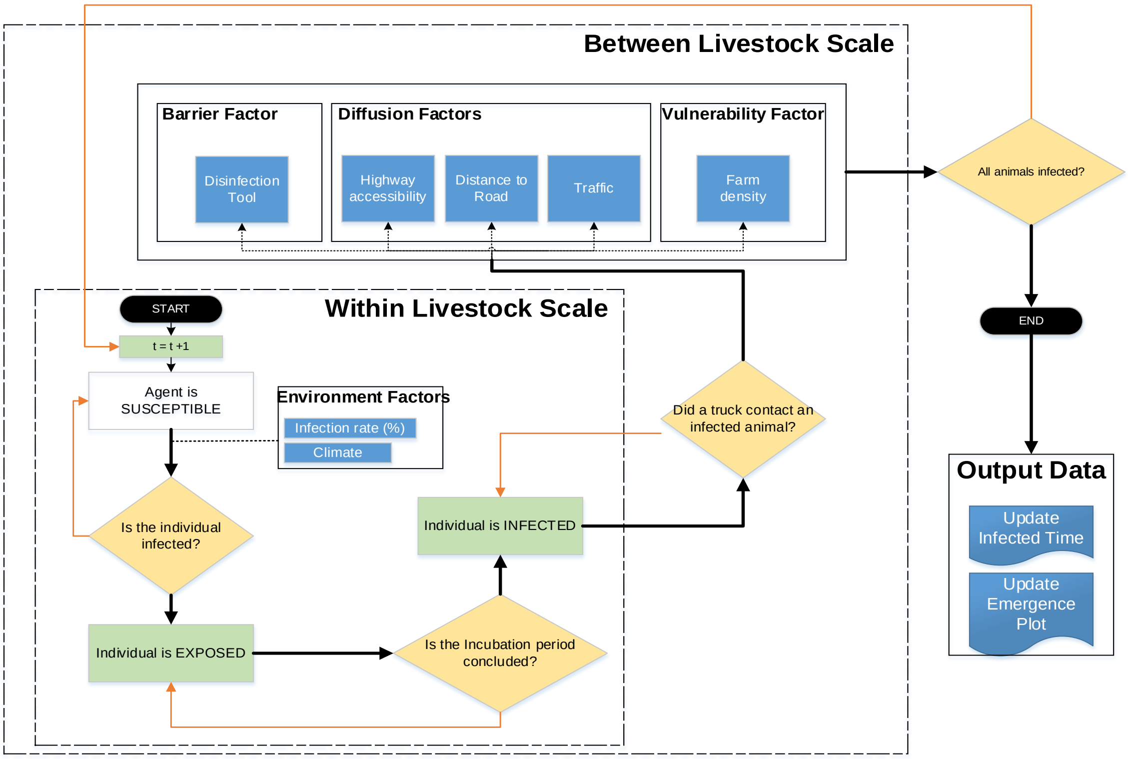


Figure 16. Process of the FMD Transmission Agent Based Model as a Single Time Step

As mentioned in subchapter 2.3, agent based model is best described by means of interactions between environment, diffusion, vulnerability, and barrier factors. The flow of FMD transmission is depicted on figure 6 which explains the spread of virus from a multi scale perspective. The agent based model is operated on discrete time steps. The daily routine is ticks/10.

Two scales are considered for the interactions in regards to transmission and emergence of the disease. One is within livestock scale where agents move, interact, and transmit in an individual scale. The other is between livestock scales, considering disease transmission between livestock through road networks.

For simulation, based on the indicators from results of spatial analysis and logistic regression a combination of five indicators were defined to represent values and their spatio-temporal process. Before proceeding combinations, sensitivity analysis is performed in which impacts of the five indicators are compared. The indicators are composed of temperature change, highway effect, road proximity, vaccine tool, and livestock density. All selected indicators have quantitative values. For each scenario, 50 model simulation were implemented to account for stochastic elements in the model. Average results are collected. A total of 72 scenarios are performed in this study. Each scenarios represent the change in human and natural environment factors in order to discover reasonable probabilities on results (Dion and Lambin 2012). Hence, the aim of this simulation is not to examine a substantive change but to produce a precautionary signal that can compare power between the indicators in the model. Dion and Lambin (2011, 2012) insists that this approach is very useful to interpret relations between simulation results. Below, this study describes how scenarios were defined in the given model.

① Temperature: Temperature values are categorised as -1°C, -51°C, -101°C. In this study -5℃ is a default value because FMD occurred and transmitted rapidly in January, which had a mean temperature of -51°C. Whereas, -1°C was selected due to KAHIS data that announced FMD outbreak happened at a temperature below 0°C, -10°C was selected as the lowest value based on monthly mean temperatures.

② Livestock density: Changes in livestock density are tested in three categories: low, medium, and high. Each categories have an amount of trucks, cows, and pigs. Firstly, the scenario related to low density obtains 5 livestock, 15 trucks, 30 cows, 45 pigs. Secondly, scenario for medium density obtains 15 livestock, 50 trucks, 100 cows, 150 pigs. Finally, scenario for high density obtains 25 livestock, 70 trucks, 140 cows, 210 pigs. The author operated numbers of animals and livestock.

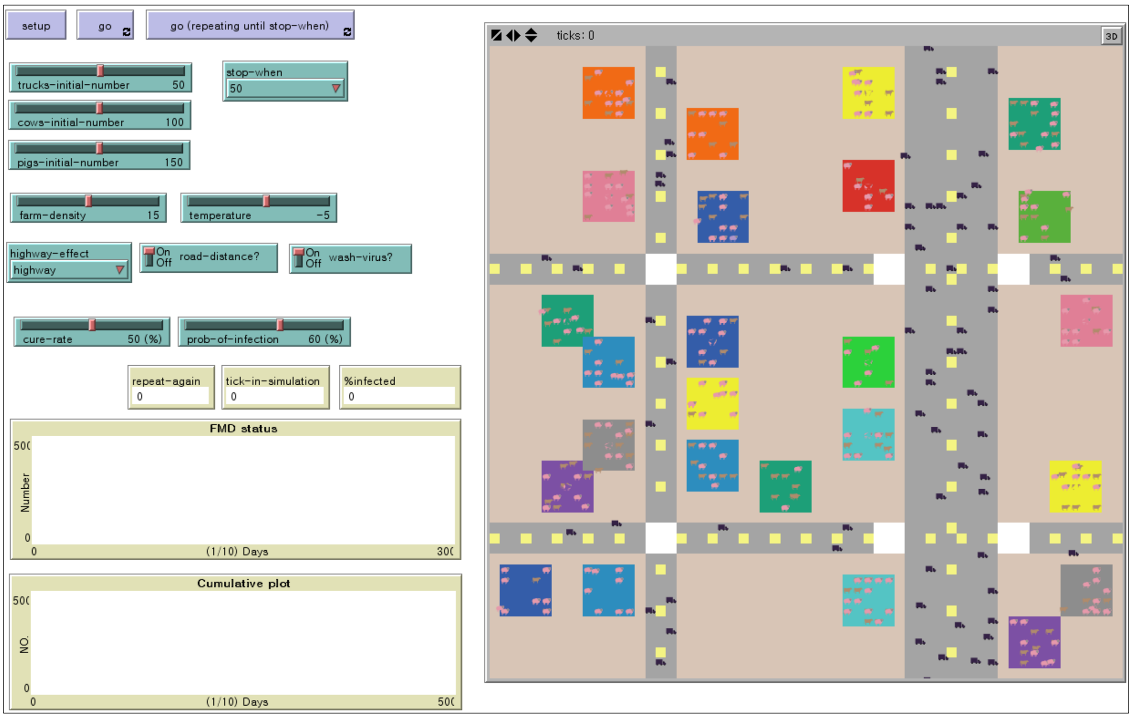
③ Highway: Two categories are simulated in order to test the velocity of vehicles on highway. Although this factor was not resulted as “statistically significant” in chapter 4, this study find highway factor significant for discovering impacts of virus transmission by road network (QIA 2011).

④ Road proximity: Two categories are designed to test effects of road proximity. Early studies show that road distance is a suitable indicator for transmission risks (Bessell *et al.* 2008).

⑤ Vaccine tool: Two categories are designed to analyse effects of sterilizers. Neither this indicator was exported from spatial analysis nor logistic regression, the author found the necessity to apply vaccine supplies by means of preventing FMD at early period (Kim 2011b).

Using the five factors, the author conducted a table for each scenario. All of the scenarios are shown in (Appendix 6, 7, and 8).

5.2.4. Simulation Toolkit



trucks-initial-number 50
cows-initial-number 100
pigs-initial-number 150
stop-when 50
farm-density 15
temperature -5
highway-effect highway
cure-rate 50 (%)
prob-of-infection 60 (%)
repeat-again 0
tick-in-simulation 0
%infected 0

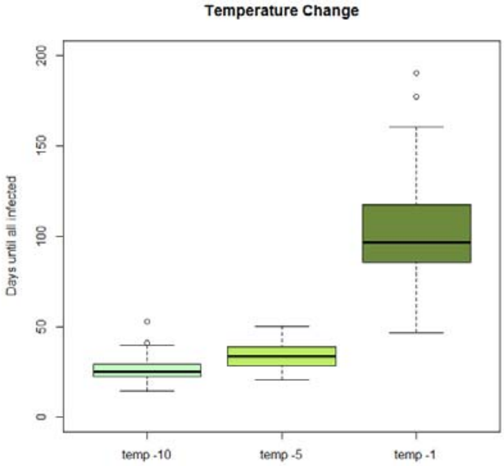
Figure 17. Interface of Agent Based SEIR Model

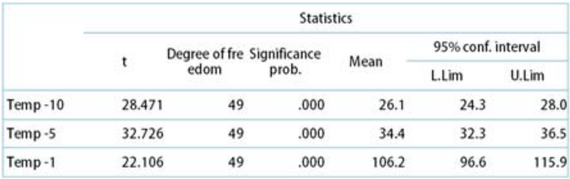
To run SEIR agent based model, Netlogo 5.0.4 is used as a toolkit. The interface is shown on figure 17. For procedure, first click setup button to make the world in vision, then click go to start simulation. Once the simulation begins, the agents move on their own designated decision. Animals move randomly in each livestock and can infect another animal. If an animal is exposed, it turns purple. After 14 days of latency period (140 ticks), 60% of agents are infected. Trucks move only on roads. When trucks meet a junction, it either turns directions or goes straight. Highway is a wide road with 1.5 times higher speeds. FMD virus are mainly disseminated through road networks. The white patch is a vaccine tool. The tool can prevent FMD infection with a probability of 50% (KAHIS 2013).

5.3. Results

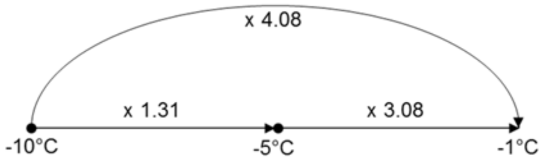
5.3.1. Sensitivity Analysis

Scenario 1: Temperature change. It takes 26.1 days for all agent to be infected in -10° C (95% C.I: 24.3 – 28.0), 34.4 days in -5° C (95% C.I: 32.3 – 36.5), and 106 days in -1° C (95% C.I: 96.6 – 115.9). Compared to -1° C (106 days), a big variation is observed at temperature -5° C, which is 3.08 times shorter. Moreover, temperature in -10° C show 4.08 times shorter than -1° C and 1.31 times shorter than -5° C. The model predicts that, at the winter season animals have a weaker immunity when the virus approaches them, and *vice versa.*

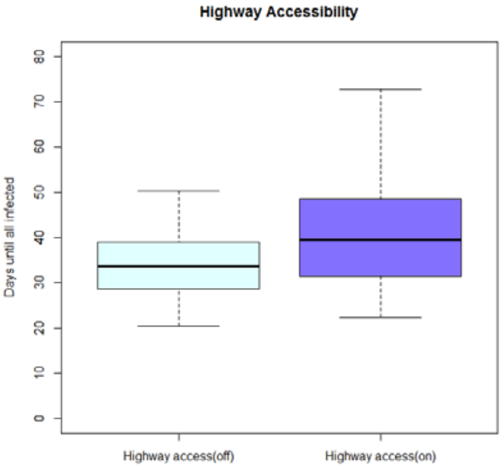


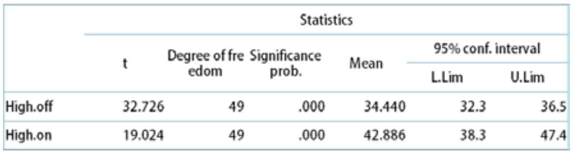


	Statistics					
	t	Degree of freedom	Significance prob.	Mean	95% conf. interval	
					L.Lim	U.Lim
Temp -10	28.471	49	.000	26.1	24.3	28.0
Temp -5	32.726	49	.000	34.4	32.3	36.5
Temp -1	22.106	49	.000	106.2	96.6	115.9



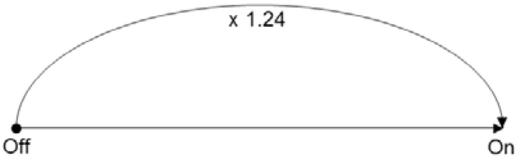
Scenario 2: Highway accessibility. Scenarios introducing highway accessibility had a weak variation from the baseline. It takes 34.4 days for all agents to be infected when the function is off (95% C.I: 32.3 – 36.5), and 42.9 days when the function is on (95% C.I: 38.3 – 47.4), which is 1.24 longer when the function is affirmative. It is hard to notice its direction due to the random movement of vehicles. In this model, simulations might not create massive variations, but a wide range of streets implicates that a good highway accessibility can possibly affect the transmission of FMD virus.



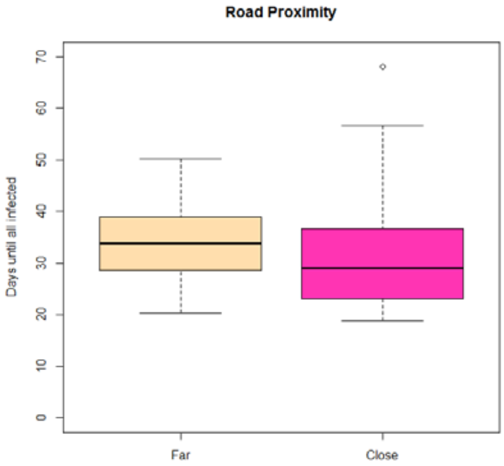


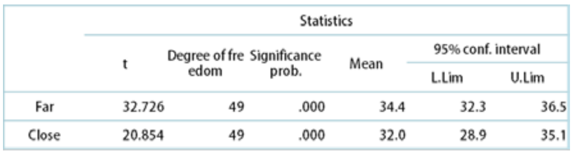
Statistics

	t	Degree of freedom	Significance prob.	Mean	95% conf. interval	
					L.Lim	U.Lim
High.off	32.726	49	.000	34.440	32.3	36.5
High.on	19.024	49	.000	42.886	38.3	47.4



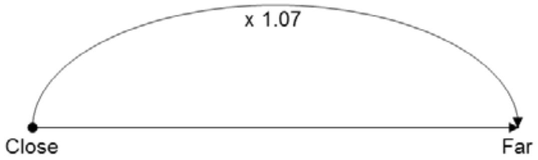
Scenario 3: Road proximity. Road proximity influenced contacts based on vehicle movement. Farms, which are far from roads, have few chances to contact vehicles, but farms adjacent to road have high possibility to get in contact with viral vehicles. It takes 34.4 days for all agents to be infected when livestock are far from roads (95% C.I: 32.3 – 36.5), and 32.0 days when livestock are close to roads (95% C.I: 28.9 – 35.1), which is 1.07 times shorter when the function is working. In the plot, the median value between these two forms is very low, which can be interpreted as: most livestock are near roads and connected to a good road network. However, we see a wide range on the left plot while the right plot is relatively narrow. This result depends on virus location and road proximity.



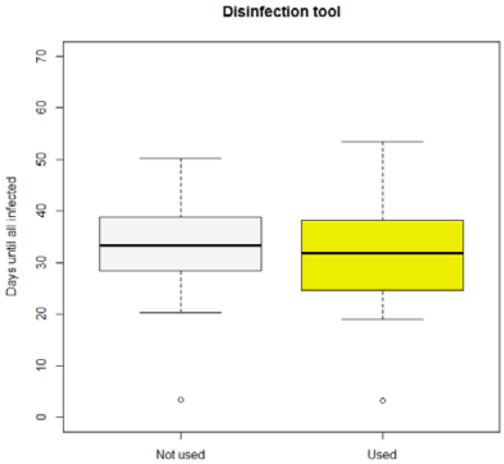


Statistics

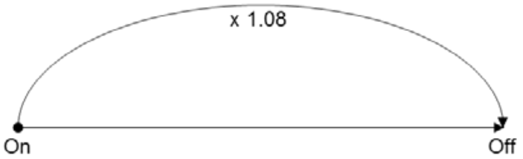
	t	Degree of freedom	Significance prob.	Mean	95% conf. interval	
					L.Lim	U.Lim
Far	32.726	49	.000	34.4	32.3	36.5
Close	20.854	49	.000	32.0	28.9	35.1



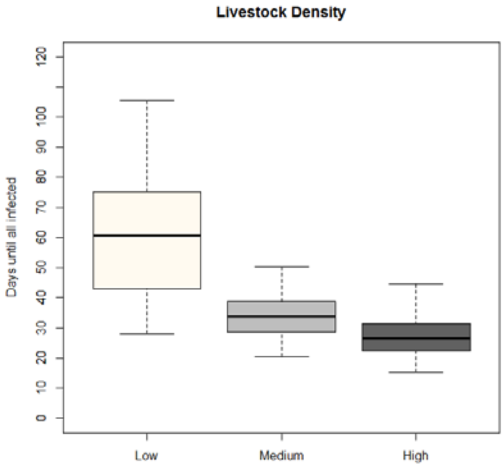
Scenario 4: Vaccine tool. The locations of sterilizers does not influence restrict disease infection greatly. It take 34.4 days for all agents to be infected when the function is off (95% C.I: 32.3 – 36.5), and 31.9 days when the function is on (95% C.I: 29.4 – 34.4), which is 1.08 times longer when vaccine tool is off. Although this tool is constructed to curb the virus down to 50%, the indicator did not show realistic changes. This is because the other factors are robust to accelerate virus dissemination before agents get treated (Dion and Lambin 2012).

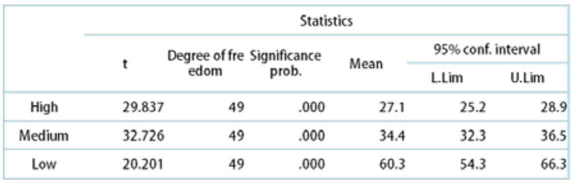


	Statistics					
	t	Degree of freedom	Significance prob.	Mean	95% conf. interval	
					L.Lim	U.Lim
Not used	32.726	49	.000	34.4	32.3	36.5
Used	25.657	49	.000	31.9	29.4	34.4



Scenario 5: Livestock density. Farm numbers associated with livestock density influenced FMD transmission. It takes 27.1 days for all agents to be infected on high density (95% C.I: 25.2 – 28.9), 34.4 days on medium density (95% C.I: 32.3 – 36.5), and 60.3 days on low density (95% C.I: 54.3 – 66.3). High livestock density takes 1.26 times shorter than that in medium density, and 2.22 times than that in low density. Medium livestock density takes 1.75 times higher than low density. Scenarios constructed with livestock density show a clear difference in the risk area.





	Statistics					
	t	Degree of freedom	Significance prob.	Mean	95% conf. interval	
					L.Lim	U.Lim
High	29.837	49	.000	27.1	25.2	28.9
Medium	32.726	49	.000	34.4	32.3	36.5
Low	20.201	49	.000	60.3	54.3	66.3

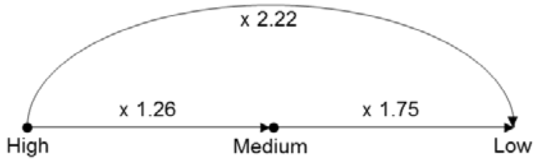


Table 13. Synthesis of Scenarios Selected

Factor	Scenario description	Result	Run time
Temperature Change	Temperature variation during winter season	Infection velocity increase when temperature decreases	-10°C:-5°C = 1.31 times -10°C:-1°C = 4.08 times -5°C :-1 °C = 3.08 times
Highway Access	Highway function on/off	Subtle difference	Off : On = 1.24 times
Road Proximity	Road proximity function on/off	Infection velocity increase when road is close to livestock	Close : Far = 1.07 times
Vaccine tool	Sterilizer on/off	Subtle difference	On : Off = 1.08 times
Livestock Density	Livestock no., animal no., truck no. increase/decrease (locations are all random)	Fast infection when density increases	High : Mid = 1.26 times High : Low = 1.75 times Mid : Low = 2.22 times

5.3.2. Combination Between Factors

To compare the relative influence of five factors, this study has several combinations of factors per scenario. A total of 72 scenarios are constructed for the analysis. This chapter initially discovers the influence of indicators that affect the speed of the epidemic period, and subsequently identifies the emergence (outbreak) of a new disease which is a breakpoint for nonlinear transmission.

5.3.2.1. Epidemic Period

The results of epidemic period, which means a 100% infection, are based on simulations for each of the scenarios. Table 13 show significant results of FMD epidemic period, which consists of rank, scenario, factor, and days until epidemic. Figure 18 present overall results of the FMD epidemic period. The combination revealed that the high ranked scenario was scenario 64, 55, 32, 30, 62, where the most influential factors are temperature and livestock density. This simulation of changing temperature and livestock density leads to 20% increase compared to default simulation (scenario 40). In addition, this simulation cannot find substantial impacts of highway accessibility, road proximity, and vaccine tool. Some of the scenarios exported a reasonable result, however these factors had a big uncertainty in the given model.

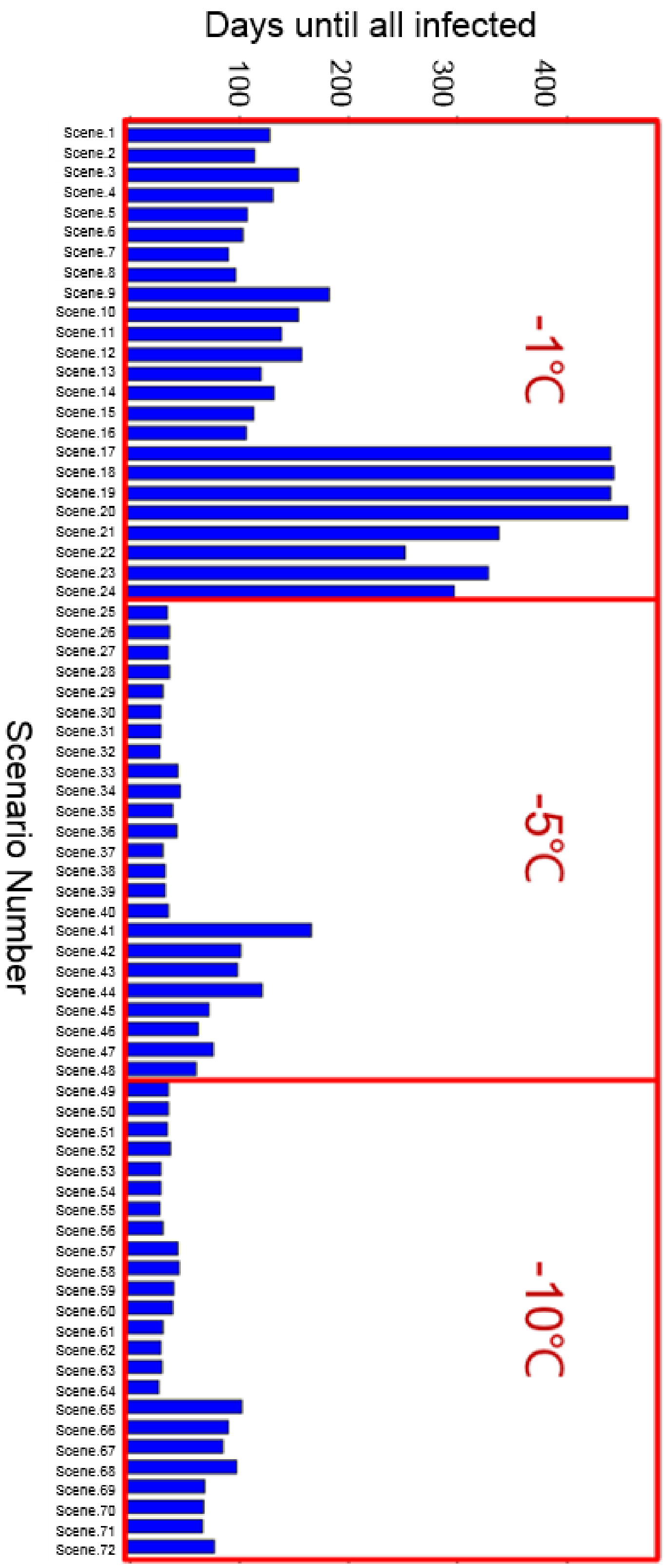


Figure 18. Simulation Results of FMD Epidemic Period (sorted by temperature)

Table 14. Results of FMD Epidemic period

Rank	Scenario	Factor	Days
1	scenario 64	Temp -10, Farm High, Highway off, road off, tool off	26.3
2	scenario 55	Temp -10, Farm High, Highway off, road off, tool on	26.9
3	scenario 32	Temp -5, Farm High, Highway off, road off, tool off	27.1
4	scenario 30	Temp -5, Farm High, Highway off, road on, tool off	27.5
5	scenario 62	Temp -10, Farm High, Highway off, road on, tool off	27.7
14	scenario 39	Temp -5, Farm Mid, Highway off, road off, tool on	32.0
15	scenario 38	Temp -5, Farm Mid, Highway on, road on, tool off	32.1
28	scenario 36	Temp -5, Farm Mid, Highway on, road off, tool off	42.9
33	scenario 48	Temp -5, Farm Low, Highway off, road off, tool off	60.3
50	scenario 16	Temp -1, Farm Mid, Highway off, road off, tool off	106.3
70	scenario 19	Temp -1, Farm Low, Highway on, road off, tool on	440.7
71	scenario 18	Temp -1, Farm Low, Highway off, road on, tool off	443.6
72	scenario 20	Temp -1, Farm Low, Highway on, road off, tool on	455.8

5.3.2.2. Emergence

Emergence is a core concept in complexity theory. In terms of disease, finding the right time of emergence can provide an effective way to restrict the spread of the epidemic. In chapter 5.2.3., the author assume that an emergence of a new disease is alerted when 30% of animal in the given world is infected (Del Valle, Mniszewski, and Hyman 2013). Figure 19 illustrates all of the scenarios in 9 groups, from A to I. Each group has 8 scenarios, which are sorted by temperature, livestock density, highway, accessibility, vaccine tool. Groups that satisfies the assumption are group D, E, F, G, H, I. Every scenario in group D, E, G, H gave a warning alert, whereas group F and I had 2 and 1 scenarios each. Unlike previous studies that insisted effects of road networks (Bessell et al. 2008, Choi et al 2012) and vaccines (Yoo 2011), this simulation results show no major impact.

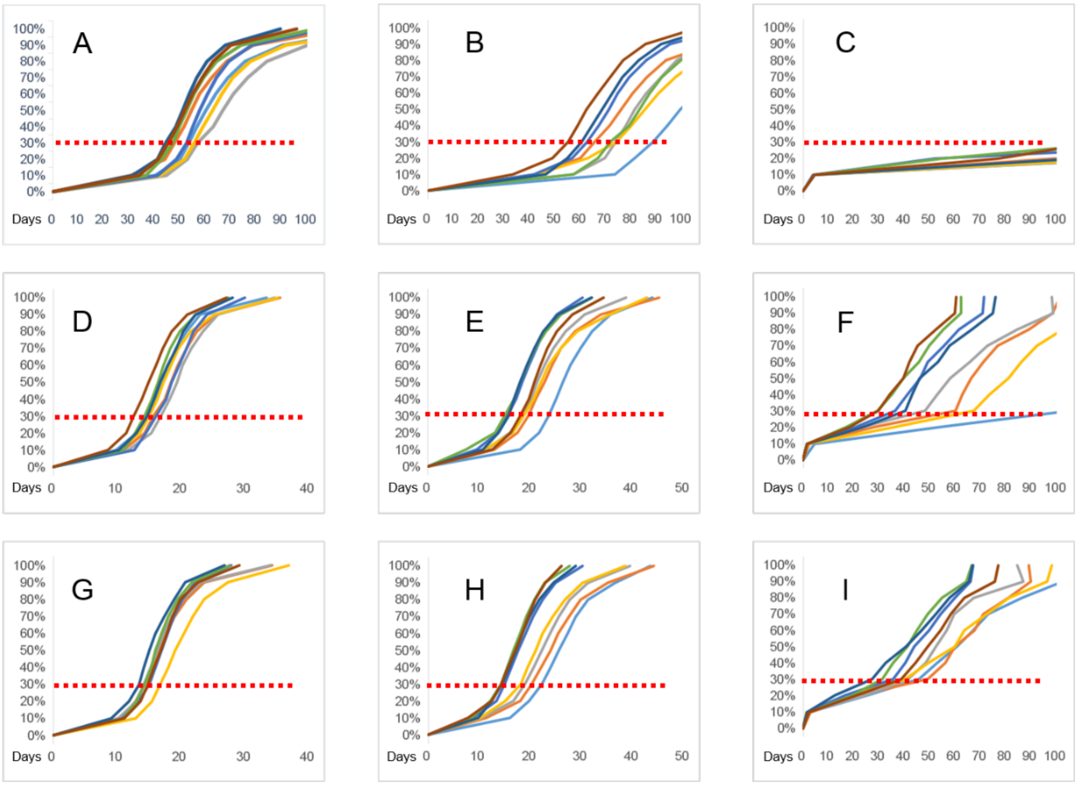


Figure 19. Scenarios of FMD Emergence

Table 14 shows results of FMD emergence that is appropriate to the emergence assumption. Emergence was reported in 35 out of 72 scenarios (48%). On average, the result for temperature has 18, and 16.6 days until emergence; 14.8, 19, 28.8 days for livestock density; 17.6 and 17.1 days for highway accessibility; 17.3 and 17.4 days for road proximity; 17.1 and 17.5 days for vaccine tool use. Note that disease emerge when temperature decreases and livestock density increases, but the other factors do not seem to change remarkably, which is relevant to epidemic period.

Table 15. Results of FMD Emergence by Each Factors

Temp.	**-1**	**-5**	**-10**		**Livestock**	**High**	**Medium**	**Low**
No. of emergences	-	18	17		No. of emergences	16	16	3
Mean of days	-	18	16.6		Mean of days	14.8	19.0	28.8

Highway acc.	**On**	**Off**	**Road prox.**	**On**	**Off**	**Vaccine**	**On**	**Off**
No. of emergences	16	19	No. of emergence	17	18	No. of emergences	17	18
Mean of days	17.6	17.1	Mean of days	17.3	17.4	Mean of days	17.1	17.5

5.4. Summary

Scenario implementations of various scenarios based on agent-based model help our understanding about spatio-temporal risk on FMD transmission. The stochastic spatial model, Netlogo, provides spatio-temporal possibilities of FMD transmission during the 2010-11 Korean epidemic. Factors (Variables) are selected as a parameter on the basis of 4.1 and 4.2, but vaccine tool is added in the simulation due to the necessity of vaccine control (QIA 2011, Yoo 2011, Muleme 2012). Although slope is an effective variable, the author does not use it because previous study indicates that there are less livestock on high altitudes, which means that slope is highly relevant to livestock density (Muleme 2012). Moreover, the author intend agents to move beyond slopes. The whole procedure in this chapter is composed of sensitivity analysis and comparisons on 72 combinations.

The spatial analysis show transmission risk of infections from livestock to other livestock, by detecting the change of each factor. In chapter 5.3.1., the variation of each factors brought different spatio-temporal results. For all agents to be infected, it takes 26.1 days in -10°C (95% C.I: 24.3 – 28.0), 34.4 days in -5°C (95% C.I: 32.3 – 36.5), and 106 days in -1°C (95% C.I: 96.6 – 115.9). Temperatures between -10° C and -1° C have 4.08 times of variation. It take 34.44 days when the function is off (95% C.I: 32.3 – 36.5), and 42.9 days when the function is on (95% C.I: 38.3 – 47.4). It take 1.24 times longer when the highway accessibility function is on. Unlike results in chapter 3, highway function passes virus infection, meaning that there are some errors in the model procedure. It takes 34.4 days when livestock are far from roads (95% C.I: 32.3 – 36.5), and 32.0 days when livestock are close to roads (95% C.I: 28.9 – 35.1), meaning a 1.07 times of variation. It take 34.4 days when the vaccine tool function is off (95% C.I: 32.3 – 36.5), and 31.9 days when the function is on (95% C.I: 29.4 – 34.4), which has 1.08 folds of variation. It takes 27.1 days on high density (95% C.I: 25.2 – 28.9), 34.4 days on medium density (95% C.I:

32.3 – 36.5), and 60.3 days on low density (95% C.I: 54.3 – 66.3). Livestock density between high and low have 2.22 times of variation. Among all input factors, temperature and livestock density modifications show reasonable results, whereas highway accessibility, road proximity, and vaccine tool do not give a good result.

To compare the relative influence of four factors (except vaccination tool), this study selects one scenario per factor that represents a comparable condition (see Table 12). The comparison reveals that the most influential factor is temperature change, which is 3rd in regression model. The other influential factor is livestock density, 1st in regression model. Third influential factor is Road proximity, 2nd in regression model. Unlike the author's opinion, highway accessibility does not function well, which is same in regression model results.

Secondly, scenarios with a combination of 5 factors indicate results in two schemes, which detect epidemic period and emergence. Results in figure 18 and table 13 show overall scenarios of epidemic period. Similar to individual results, high ranked scenarios tend to have low temperature and high livestock density. These results sufficiently support National Veterinary Research & Quarantine Service Epidemiological report (2011), which insist livestock density, cold weather, and road network as a reason. Compared to individual models (scenario 16, 36, 38, 39, 48), it is realised that model combinations can predict FMD transmission under various conditions.

The second scheme is analysing the emergence of FMD disease. As a result, 35 scenarios out of 72 scenarios are appropriate to the given assumption. In table 14, it is found that if the temperature decreases, the number of scenarios increases nonlinearly while epidemic period decreases in a nonlinear pattern. Livestock density acts *vice versa.* However, scenarios with highway accessibility, road proximity, and vaccine tool does not have substantive difference from scenarios that do not use it. Although this study do not compare effectiveness in road factors, this simulation results are useful in providing estimates of the efforts on disease problems and it delivers insights towards potential risk effects on the dynamics of disease transmission (Muleme 2012, Choi et al 2012). Like FMD, many of the microbial pathogens are likely to be deadly contagious. In spite of vaccine effects, this model can necessarily be a good option for preparing antiviral therapies that can play a significant role in preventing any outbreaks. Furthermore, it is found that scenarios that reach the emergence level in short period tend to be epidemic in short time. This finding is so-called emergence, the fact that infectious diseases explosively transmits after a break point.

This study argues that models which combine low temperature and high livestock density are more likely to explain the dynamics of FMD transmission than models that ignore combination of these factors. Although these factors cannot explain everything, it is recognised that these adjustments may well have potential to slow down the spread of FMD transmission.

From this simulation, we implicate that complexity system is difficult to interpret because subtle modification in an individual can produce massive difference in the risk of FMD (Dion, VanSchalkwyk, and Lambin 2011, Dion and Lambin 2012). For instance, we can clearly detect the difference at the temperature of -1° C and -10° C in the simulation. In addition, this model shows advantages of incorporating various factors in one scenario as a synthetic perspective and discovering temporal and visual progresses in the model.

6. DISCUSSION AND CONCLUSION

In November 2010, foot-and-mouth disease (FMD) occurred in South Korea leading 75 infected cities and 3.5 million slaughtered animals. This epidemic is derived from several reasons including failure in early detection, movement behaviour of agents, and external environments. Recognising the main factors for FMD transmission, this study demonstrates the impact of factors that affect FMD transmission during the 2010-11 Korean epidemic. The study argues that models which use agent behaviour and modification of external environments are better able to capture the influence of FMD transmission process. Previous studies on veterinary science, disease ecology, and spatial diffusion theory are reviewed to investigate the transmission patterns and factors of FMD. In addition, a review of agent-based model is reviewed as a basic method for this research.

In order to demonstrate the effectiveness of the selected factors, the current study is conducted into 3 schemes, which are 1) examining spatial transmission process and factors of FMD, 2) investigating risk factors that affect the spatial spread of FMD, and 3) discovering impacts of potential factors that control FMD transmission speed. Below are the key findings of the research themes.

First, this study aims to examine spatial transmission process and factors of FMD epidemic. Ordinary kriging interpolation, slope calculation, and multiple ring buffer tool is used as a method. Initially, the result finds FMD transmission direction which had spread throughout the country where it initially occurred in the south-eastern region, moved to the northwest, moved to the eastern region, came back south, and finally ended in south-eastern region. The second findings are the spatial factors related to FMD, such as 1) temperature during winter season is a good condition for outbreak and temperature variation is estimated for FMD transmission 2) compared to temperatures, humidity does not show a substantive difference, but we see that 60% of the cities satisfy the condition in 2010-11; 3) result of slope describes that livestock located in low lands have a good probability for having FMD transmission; 4) results of road data describe that 77% of FMD outbreak points are close to general roads; and 5) 77 percent of FMD outbreaks are close to highway entrance. There are other possible reasons associated with FMD, including political matters, veterinary misdiagnosis, tourism, and foreign workers. However, these parameters are hard to be converted into numerical value in this study. Nevertheless, by using spatial analysis, these key factors give intuitive risk information.

Second, this study investigates the risk factors that affect FMD transmission. A case and control method is used as a method. Factors including livestock density (vulnerability factor); slope, temperature, humidity (environment factor); highway accessibility, and road proximity (diffusion factor) are selected. The odds ratio of case cities having the factor livestock density (1.38 times), highway accessibility (1.35 times), was significantly higher than control cities, whereas temperature (0.47 times), humidity (0.87 times), slope (0.82 times), and road distance' (0.45 times) resulted in opposite. To identify the strength between each variables, Wald statistics are provided for examination. Variables are ranked: 1) 'livestock density', 2) road distance, 3) slope 4) humidity, 5) temperature, 6) highway accessibility in order. Although humidity and highway accessibility have no impact on the risk of FMD transmission, livestock density, road distance, slope, and temperature are statistically significant in this model. Overall model has a good fit showing 18.1 chi-square points and $p < 0.0006$ value. In this study, FMD disease has a chance to spread by the unrestricted movements of vehicles, high density of livestock location, low degree of slope, and in low temperature.

The author notes the possible biases due to the case-and-control study. Although case and control cities have 93 cities in total, cities that have missing data due to a cultivating area below 1km. Environment factors are interpolated based on kriging method, so error rate from AWS points will be considered in this circumstance. On the other hand, the statistical results provide information about cause and effect between risk factors and disease outbreak. Therefore, effects between variables are sufficient to validate. To strengthen this argument, further research such as adding survey data are needed. According to Muroga *et al.* (2013), lots of survey and paper-based records can minimize analysis bias.

Third, this study discovers the impact of determine factors that influence FMD transmission speed based on agent based model. Agent-based SEIR model is conducted in this study to simulate FMD transmission via direct and indirect impacts on the movement of animals and vehicles. 5 key variables including temperature, livestock density, highway accessibility, road proximity, and vaccine tool are selected for implementation. Slope is not considered as a key parameter because the author thought FMD occurs at low slope in which livestock density is high, and want to move agents in random. A 2-level simulation is implemented, which is first sensitivity analysis and secondly is combination analysis. The sensitivity analysis results detect differences on FMD transmission speed by changing each factors. Compared to -1°C, temperature change takes 4.08 times shorter in -10°C environment, which is followed by livestock density which has 2.22 times of variation between high and low. Road proximity, and vaccine tool show weak effect, which results 1.07 and 1.08 times of variance. Unfortunately, when highway accessibility is affirmative it takes 1.24 times slower to 100% infection. Run time variation of factors are ranked as 1) Temperature 2) Livestock density, 3) Road proximity, and 4) Highway accessibility. Compared to statistic results, this simulation verifies temperature and livestock formation as a critical factor on FMD transmission.

The second implement is combining all 5 of elements in the model. A total of 72 scenarios is simulated. The first progress is comparing epidemic period (i.e. 100%

infection) in all of the scenarios. Combination result reveals that high ranked scenario have factors that contain low temperature and high livestock density. Highway accessibility, road proximity, and vaccine tool does not show a remarkable difference. The second progress is analysing the emergence of FMD disease. As a result, 35 scenarios out of 72 scenarios are appropriate to the given assumption. As temperature decrease, the number of scenarios which show emergence pattern increase in a nonlinear pattern. Livestock density acts *vice versa*. Road proximity and vaccine tool show a fine difference when it activated, whereas highway accessibility does not show substantive difference in the scenario table. Although every factor is not considered in the model procedure, the result notifies that a mixture of low temperature and high livestock density modification have potential risk to generate FMD transmission.

In some scenarios, the system does not always change in an intuitive pattern (e.g., scenarios associated with highway accessibility, road proximity, and vaccine tool). Nevertheless, this implementation is important because uncertainties, considered in the model outcomes, are often ignored but they exist in the real world (Gatrell 2005, Liliana and Suzana 2009). In addition, the model shows advantages of incorporating various factors in one scenario as a synthetic perspective and discovering temporal and visual progresses in the model. Moreover, we could realise that spatio-temporal behaviours of environment and human have the potential to generate FMD epidemic. This result raises questions about the behaviour of peoples acted in the last epidemics. Roles of the national government, local government, and citizens from the previous event during 2010-11 FMD epidemic should be documented (Kim 2011a, Kim 2011b).

On the basis of the study, it was expected that the spatio-temporal transmission of FMD would proceed through regions of low temperature, low slope, high livestock density, great highway accessibility and road proximity. Although slope was statistically significant factor for FMD transmission, this study did not input this to ABM simulation because random slopes in every sequence is impossible in a virtual world. Muleme (2012) notified that people tend to build livestock breeding farm in lower altitude in order to communicate closely with livestock markets. Unfortunately, highway accessibility, which was thought as the most important factor (Bessell et al. 2008, QIA 2011), is discovered neither statistically significant nor highly effective in ABM simulation. Results for statistical result exceed the significance level because the sources had limits by counting 0 and 1 as an accessibility indicator, and the movement of vehicles were not ordered to slow down when it met an interchange. Some delicate problems have to be modified for a better model. Sterilisers (i.e. vaccine) in ABM model were set on each junctions having 50% cure rate (KAHIS 2013). Since antiviruses are expensive and are produced in few countries including France, Germany, The Netherlands, and UK, The Korean Animal and Plan Quarantine Agency can only purchase a limited amount of sterilisers. FAO Animal Health Manual required antivirus effect up to 80% (Geering and Lubroth 2002). If the antivirus can increase its effect up to 80%, we can increase steriliser effect on this model. Since the model was an experimental (virtual) model, this study did not consider geographic barriers such as slope, railroads, and rivers. Further studies based on GIS-ABM can give accurate insight on disease surveillance.

Findings of this study can be effective in reducing animal mortality, economic damage, and slowing FMD transmission. There are three suggestions. First, livestock owners should be aware of FMD dissemination normally in the beginning of winter season. Regular confirm in livestock and close examination is required. This study raises an idea about including environment change (e.g. temperature and humidity) into the national disease surveillance.

Second, this study suggests the need for limiting livestock density. From the statistical and scenario results, livestock density is depicted a great impact on FMD transmission. Results of previous studies (Geering and Lubroth 2002, Verma et al. 2008, Muroga et al. 2013) support this idea indicating that livestock with high density tend to infect another adjacent livestock. As FAO strategies for FMD eradication, "Reducing the number of infected or potentially infected animals in livestock populations", the government should adjust the current legislation by limiting animal populations in each farm or creating new livestock breeding farm over a certain distance.

Third, findings of this study may be feasible to develop influenza vaccination on priority risk areas. Common strategies set territorial rings for ring vaccination or ring culling (Yoon et al. 2006). Although this study gave insights of alternative control strategies by a creating diameter control area in a stochastic simulation model (InterSpread Plus), practical stakeholders will proceed policies in administrative areas rather than the circle to implement control measures (Rivas et al. 2006). This study may have benefits by suggesting accurate vaccine tool locations from various scenarios. For example, simulations for vaccine tool can be set up on junctions near large livestock areas (e.g. Andong, Hoengsung, Paju, Yeonchon etc.): within 1km; 1km to 3km; 3km to 5km. Otherwise, vehicles which move to markets or high populated cities could be subjected to regular inspection. It is practically possible to increase the chance of vaccine treatment, but since antivirus supply is limited to cover all of the country, we can develop this model to prevent potential virus spread in the future.

Early detection of alternative scenarios and early transmission warning to the public can empower the livestock owners, car drivers, and the whole nation to make feasible guidelines (Kim 2011b, Del Valle, Mniszewski, and Hyman 2013). It is evident from the experience of the 2010-11 FMD disaster that our awareness of infectious disease, supply of vaccine drugs, capabilities to predict better the annual vaccine production remained inadequate (Kim 2011a, Kim 2011b, QIA 2011). However, most emerging infections these days may truly give new threats if the nation or world is inadequately prepared. Recognising these vulnerabilities, it is necessary for scientific and financial investments as well as international cooperation to strengthen defence against the future threats. As previous studies argue, preparing scientific surveillance tools, listening to what farmers say, and establishing a citizen surveillance team are good and realistic approaches to prevent FMD infection (Nerlich, Hamilton, and Rowe 2002, Kim 2011b, Convery et al. 2008).

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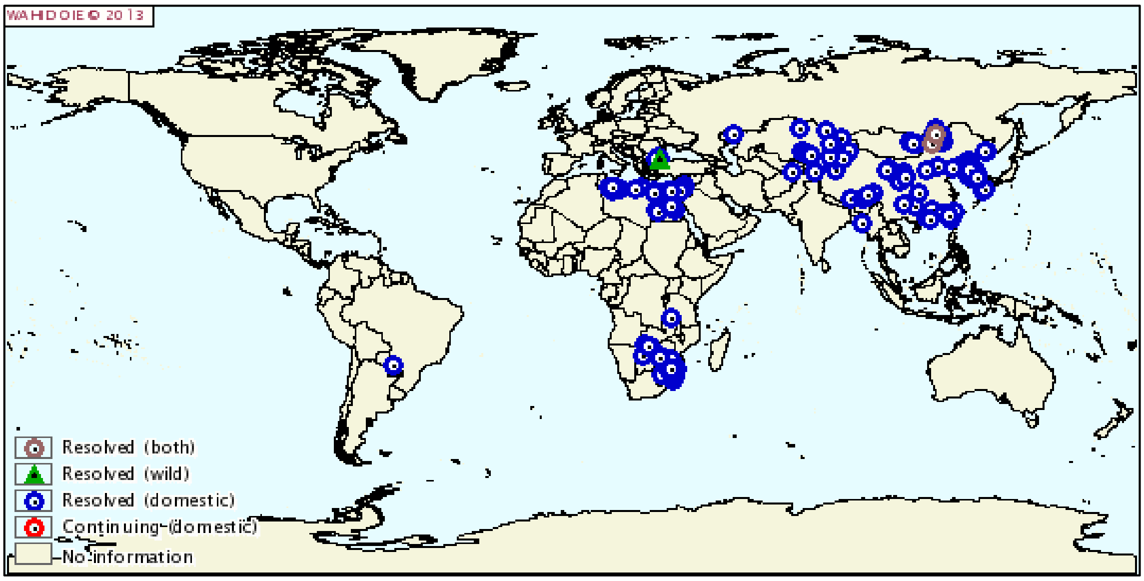
APPENDIX

Appendix 1. Disease outbreak map of FMD (2010-2012) (WAHID)



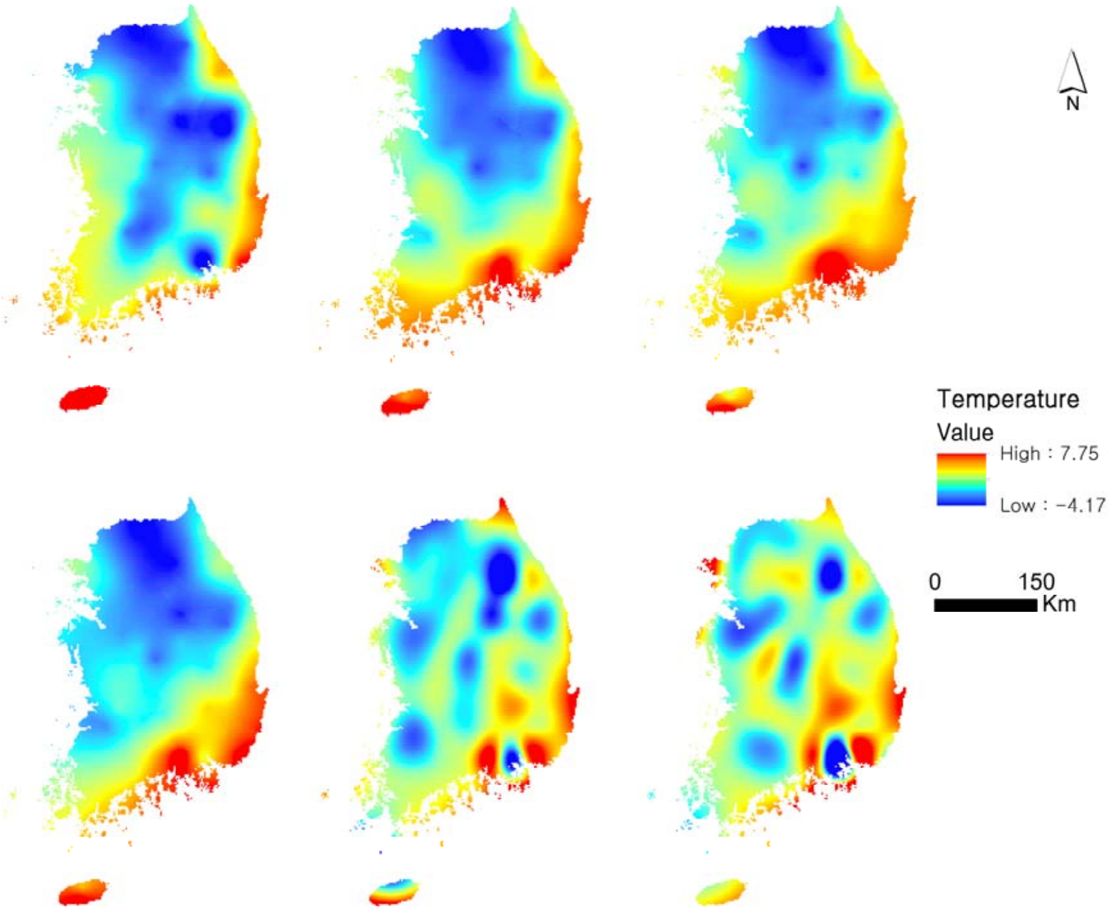
Appendix 2. FMD Outbreak Countries

Continent	Countries
Asia (36/48)	Afghanistan, Bahrain, Bhutan, Cambodia, China, Chinese Taipei, India, Iran, Iraq, Israel, Japan, Kazakhstan, North Korea, South Korea, Kuwait, Kyrgyzstan, Laos, Lebanon, Malaysia, Mongolia, Myanmar, Nepal, Oman, Qatar, Saudi Arabia, Sri Lanka, Syria, Tajikistan, Thailand, The Philippines, United Arab Emirates, Vietnam, Yemen
Africa (33/52)	Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Central African Republic, Chad, Comoros, Congo (Dem. Rep. of the), Cote D'Ivoire, Egypt, Eritrea, Ethiopia, Ghana, Kenya, Malawi, Mali, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal, Somalia, South Africa, Sudan, Tanzania, Togo, Uganda, Zambia, Zimbabwe
America (3/55)	Ecuador, Paraguay, Venezuela
Europe (3/50)	Bulgaria, Russia, Turkey

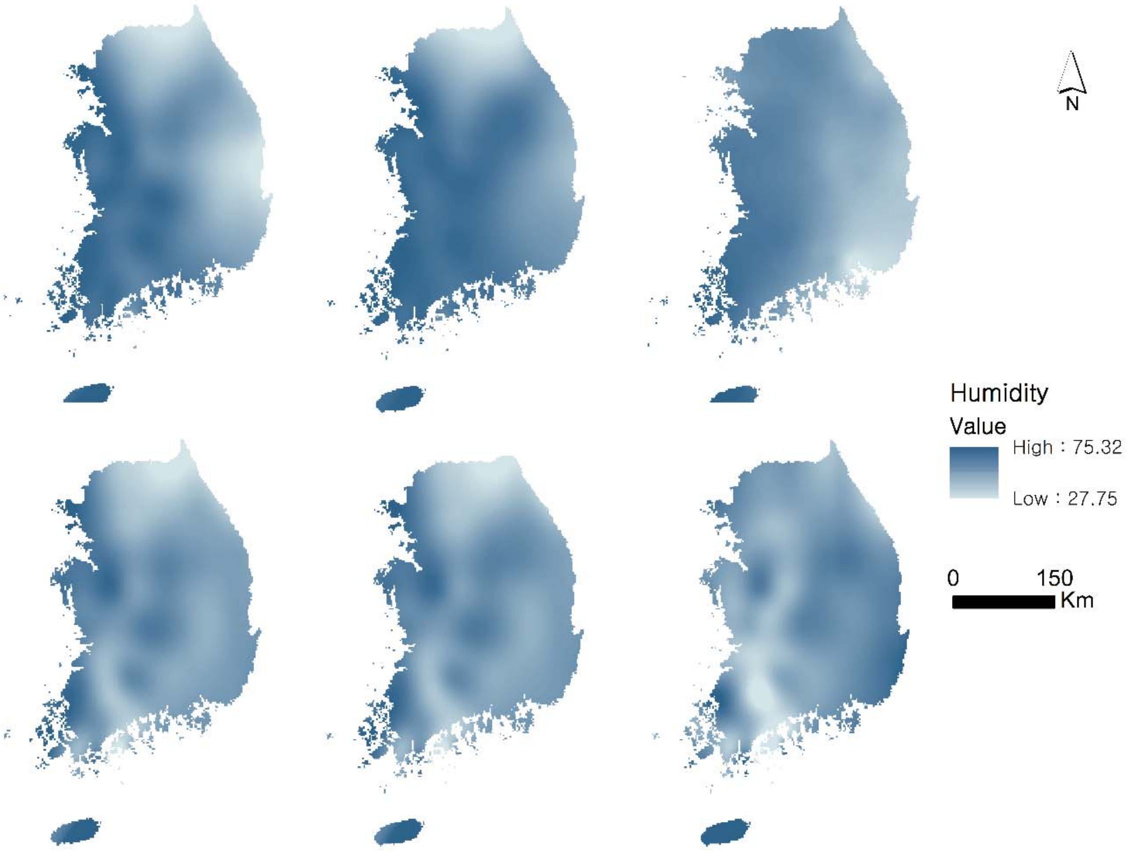
Appendix 3. FMD outbreak after 2000 (reconstitute from National Vet Research, 2011)

	2000	**2002**	**2010.1**	**2010.4**	**2010.11**
Initially infected farm	2000.3.24 Paju 15 dairy cattle	2002.5.2 Anseong 8022 pigs	2010.1.2 Pocheon 198 dairy cattle	2010.4.8 Ganghwa 177 cows	2010.11.28 Andong
Period	2000.3.24.-4.15 (23 days)	2002.5.2-6.23 (53 days)	2010.1.2~1.29 (28 days)	2010.4.8~5.6 (29 days)	10.11.28-11.04.24 (144 Days)
Location	6 cities (Paju, Hwaseong, Yongin, Honseong, Boryung, Chungju)	4 cities (Anseong, Yongin, Pyeongtaek, Jincheon)	2 cities (Pocheon, Yeoncheon)	4 cities Ganghwa, Gimpo, Chungju, Chungyang	75 cities
Virus type	Pan Asia O_1	Pan Asia O_1	A type (Asia)	O type (SEA)	O type (SEA)
Animals killed	2,216	160,155	5,360	3,911	3,479,962
Finance expenditure	348 billion KRW	165 billion KRW	336 billion KRW	143 billion KRW	3 trillion KRW

Appendix 4. Monthly temperature 2010-11



Appendix 5. Monthly humidity 2010-11



Appendix 6 Synthesis of scenarios for agent based model

	Temperature	Farm density	Highway	Road prox	Sterilizer
1	-1℃	上	1	1	1
2	-1℃	上	1	1	0
3	-1℃	上	1	0	1
4	-1℃	上	1	0	0
5	-1℃	上	0	1	1
6	-1℃	上	0	1	0
7	-1℃	上	0	0	1
8	-1℃	上	0	0	0
9	-1℃	中	1	1	1
10	-1℃	中	1	1	0
11	-1℃	中	1	0	1
12	-1℃	中	1	0	0
13	-1℃	中	0	1	1
14	-1℃	中	0	1	0
15	-1℃	中	0	0	1
16	-1℃	中	0	0	0
17	-1℃	下	1	1	1
18	-1℃	下	1	1	0
19	-1℃	下	1	0	1
20	-1℃	下	1	0	0
21	-1℃	下	0	1	1
22	-1℃	下	0	1	0
23	-1℃	下	0	0	1
24	-1℃	下	0	0	0

Appendix 6 Synthesis of scenarios for agent based model

	Temperature	Farm density	Highway	Road prox	Sterilizer
1	-1℃	上	1	1	1
2	-1℃	上	1	1	0
3	-1℃	上	1	0	1
4	-1℃	上	1	0	0
5	-1℃	上	0	1	1
6	-1℃	上	0	1	0
7	-1℃	上	0	0	1
8	-1℃	上	0	0	0
9	-1℃	中	1	1	1
10	-1℃	中	1	1	0
11	-1℃	中	1	0	1
12	-1℃	中	1	0	0
13	-1℃	中	0	1	1
14	-1℃	中	0	1	0
15	-1℃	中	0	0	1
16	-1℃	中	0	0	0
17	-1℃	下	1	1	1
18	-1℃	下	1	1	0
19	-1℃	下	1	0	1
20	-1℃	下	1	0	0
21	-1℃	下	0	1	1
22	-1℃	下	0	1	0
23	-1℃	下	0	0	1
24	-1℃	下	0	0	0

Appendix 7. Synthesis of scenarios for agent based model (continue)

	Temperature	Farm density	Highway	Road prox	Sterilizer
25	-5 ℃	上	1	1	1
26	-5 ℃	上	1	1	0
27	-5 ℃	上	1	0	1
28	-5 ℃	上	1	0	0
29	-5 ℃	上	0	1	1
30	-5 ℃	上	0	1	0
31	-5 ℃	上	0	0	1
32	-5 ℃	上	0	0	0
33	-5 ℃	中	1	1	1
34	-5 ℃	中	1	1	0
35	-5 ℃	中	1	0	1
36	-5 ℃	中	1	0	0
37	-5 ℃	中	0	1	1
38	-5 ℃	中	0	1	0
39	-5 ℃	中	0	0	1
40	-5 ℃	中	0	0	0
41	-5 ℃	下	1	1	1
42	-5 ℃	下	1	1	0
43	-5 ℃	下	1	0	1
44	-5 ℃	下	1	0	0
45	-5 ℃	下	0	1	1
46	-5 ℃	下	0	1	0
47	-5 ℃	下	0	0	1
48	-5 ℃	下	0	0	0

Appendix 8. Synthesis of scenarios for agent based model (continue)

	Temperature	Farm density	Highway	Road prox	Sterilizer
49	-10℃	上	1	1	1
50	-10℃	上	1	1	0
51	-10℃	上	1	0	1
52	-10℃	上	1	0	0
53	-10℃	上	0	1	1
54	-10℃	上	0	1	0
55	-10℃	上	0	0	1
56	-10℃	上	0	0	0
57	-10℃	中	1	1	1
58	-10℃	中	1	1	0
59	-10℃	中	1	0	1
60	-10℃	中	1	0	0
61	-10℃	中	0	1	1
62	-10℃	中	0	1	0
63	-10℃	中	0	0	1
64	-10℃	中	0	0	0
65	-10℃	下	1	1	1
66	-10℃	下	1	1	0
67	-10℃	下	1	0	1
68	-10℃	下	1	0	0
69	-10℃	下	0	1	1
70	-10℃	下	0	1	0
71	-10℃	下	0	0	1
72	-10℃	下	0	0	0

국문초록

2010 년 발생한 구제역 사태는 11 월 28 일 경북 안동에서 시작되어 2011 년 4 월 21 일까지 전국 11 개 시도, 75 개 시 · 군 · 구로 확산되었다. 국립수의과학검역원은 2010 년 말에 발생한 구제역이 과거와 다르게 전국적으로 발생하고 있는 주요요인으로 최초 발생 농장의 신고 이후 지방자치단체 방역기관의 초기 대응이 미흡했던 점, 안동지역에서 최초로 확진되기 이전에 이미 경기도 지역으로 전파되었다는 점, 추운 날씨 등으로 방역에 어려움이 있었던 점을 들었다. 그 결과 구제역으로 전국 4200 개 매몰지에 소 15 만 두, 돼지 331 만 두 등 총 348 만 여 두가 살처분 및 매몰되었고 매몰보상금으로 18,617 여 억원의 개인 및 국가적인 천문학적 피해가 발생하였다. 구제역과 같은 심각한 전염병은 초기 방역에 실패할 경우 농가에 2 차 혹은 3 차에 걸친 피해가 발생하고 우유나 고기 생산량 저하에 따라 소비자도 영향을 받는다. 이 때문에 역학조사작업은 피해발생을 예측하고 예방하기 위해 무엇보다 시급히 이루어져야 할 연구과제이다.

구제역처럼 다양한 요인과 경로를 통한 전염병의 확산은 복잡한 과정을 거친다. 이에 최근 전염병의 상호작용과 확산을 복잡계 이론으로 해석하는 연구들이 많아졌다. 복잡계 네트워크 안에서 전염병은 질병의 중심성과 연결성, 그리고 행위자 사이의 상호작용 구조에 따라 창발(emergence)이 일어나는 결과가 달라지기 때문에 연구할 가치가 있다. 따라서 이 연구의 목적은 행위자와 외부환경의 상호작용이 구제역의 시공간 확산에 어떠한 영향을 미치는지를 규명하고자 하는 것이다. 세부목적은 다음과 같다. 첫째, 구제역의 공간확산과정과 요인을 알아본다. 둘째, 구제역 확산의 인과관계를 규명한다. 셋째, 구제역의 시공간 확산 속도를 조절하는 결정요인들을 규명한다. 연구방법은 세부목적의 순서대로 공간분석, 위험 대조군 분석, 행위자기반모형을 사용하였다. 연구결과는 다음과 같다.

첫째, 공간확산 과정과 요인을 분석한 결과, 구제역의 확산방향과 창발의 건수를 시각적으로 확인할 수 있었고 2010-11 년 당시의 기온, 습도, 도로와의 거리, 경사와 구제역 발생지점 간의 관계를 파악할 수 있었다.

둘째, 구제역 확산의 인과관계를 분석한 결과, 기온, 습도, 경사, 농장밀도, 고속도로와의 거리, 도로와의 거리가 변수로 사용되었다. 이중에서 기온, 경사, 농장밀도, 도로와의 근접성이 유용한 변수로 추출이 되었다. 모델의 전체적인 적합성은 95% 유의수준에서 chi-square 값이 18.1 로 유의하였고, P-value 도 0.0006 으로 유의미하였다.

셋째, 구제역의 시공간 확산 속도를 조절하는 결정요인들을 규명하기 위해서 앞선 공간분석의 결과와 통계분석의 결과로 얻은 변수를 반영하였다. 여기에 기온, 농장밀도, 고속도로와의 접근성, 도로와의 거리, 방역여부가 선정되었다. 방역 변수는 앞의 분석에서 밝혀지지 않았지만 역학 혹은 정책적으로 필요하다고 판단하여 추가하였다. 총 72 개의 시나리오로 분석한 결과, 기온변화와 농장밀도의 변화가 구제역의 공간적 확산에 주요한 영향을 미치는 것으로 나타났다. 나머지 변수에서는 뚜렷한 변화가 포착되지 않았다. 이는 모델 구성과정에서 오류로 남아 있을 수 있고, 역학보고서에서 그 수치가 반영이 제대로 안되었기 때문일 수 있다.

이 연구는 구제역의 확산에 영향을 주는 인자들의 효과성을 알아보기 위한 연구이며, 그 기본전제는 행위자와 외부환경의 상호작용이었다. 이 연구에서는 외부환경의 변화와 행위자들의 행태에 따라 구제역의 시공간적 확산패턴에 차이가 존재한다는 것을 밝혔다. 이 연구에는 연구자료, 모델의 설계과정, 혹은 프로그램의 기계적 오류 등의 한계가 존재한다. 이를 유의하여 결과를 해석하였을 때, 기온이 낮은 겨울철에 접근성이 높은 대농장 지역의 구제역 확산 가능성이 높으므로 구제역 예방 정책 수립 시 우선순위가 될 수 있을 것이다. 이 연구는 질병의 확산과 방역과정의 의사결정 시스템으로서 의의를 가지며, 향후 모델의 개선을 통해 질병 확산을 예방하는 데 기여할 수 있을 것이다.