NOTE *Virology*

Evaluation of the transmission risk of foot-and-mouth disease in Japan

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ABSTRACT. The transmission risk of foot-and-mouth disease (FMD) in Japan was evaluated using a mathematical FMD transmission model. The distance-based transmission rate between farms, which was parameterized using the FMD epidemic data in 2010 in Japan, was used to calculate the local-level reproduction numbers—expected numbers of secondary infections caused by one infected farm—for all cattle and pig farms in the country, which were then visualized as a risk map. The risk map demonstrated the spatial heterogeneity of transmission risk in the country and identified risk areas with higher possibility of disease spread. This result suggests that, particularly in high-risk areas, it is important to prepare for the smooth and efficient implementation of control measures against FMD outbreaks.

KEY WORDS: FMD, Japan, risk map, transmission kernel, transmission risk

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An outbreak of foot-and-mouth disease (FMD) occurred in Japan in 2010. Because of the high density of cattle and pigs in the affected area [11, 14], the disease spread rapidly and extensively. The epidemic lasted 3 months, during which 292 farms were infected and almost 290,000 animals kept on infected or vaccinated farms were culled, causing devastating damage to the livestock industries in the area. In this large FMD epidemic, the attributes of the affected area, which has a high density of cattle and pig farms, are considered to have influenced the epidemic pattern of FMD [14]. Because the susceptibility and transmissibility of FMD differ among animal species [1, 8, 18], it is important to consider the characteristics of an epidemic area, such as farm density and animal species, to determine the transmission risk of the disease. In this study, to provide a basis for the development of preparedness for future outbreaks of FMD, the transmission risk of FMD in Japan was evaluated using a mathematical model of the spread of FMD, and then, the risk in each area was visualized as a geographic risk map that identified high-risk areas for FMD transmission.

To evaluate the transmission risk of FMD in the country, farm information, including spatial location, animal species (cattle or pig) and farm size, was obtained from the database of the Animal Health Division of the Ministry of Agriculture, Fisheries and Forestry (MAFF) in Japan. At the time of data collection in July 2014, 89,826 farms (83,324 cattle farms and 6,502 pig farms) in the 47 prefectures were included in the database. The summary of farm information used in this study is shown in a Supplementary Table 1. Farm size data in the database were used to evaluate the transmission risk of FMD. However, because almost 10% of farms did not include the actual farm size in the database, the average number of animals per farm by animal species in the prefecture in which the farms were located, which was derived from the livestock industry statistics published by MAFF in 2013 [13], was alternatively used for those farms.

The local farm-level reproduction number R_i, which is defined as the expected number of secondary infections caused by one primary infectious farm i throughout its infectious period in a population of susceptible farms, was calculated to measure the risk of between-farm transmission under movement restrictions. The same approach has been applied for risk maps of FMD or avian influenza in previous studies [3, 4, 6, 19]. When the transmission rate at which infectious farm i causes infection on a susceptible farm j on a given day is defined as r_{ij}, r_{ij} is calculated as follows:

$$r_{ij} = c_{mn} N_i N_j k\left(d_{ij}\right)$$

where N_i and N_j are the logarithmic number of animals on the infectious farm i and the susceptible farm j, c_{mn} refers to the transmission coefficient, a parameter that accounts for the species-specific transmissibility (subscripts m and n corresponding to the animal species on the infectious farm i and the susceptible farm j, respectively; for example, the transmission coefficient for cattle-to-pig farms is written as c_{cp} by indicating the cattle farm and pig farm subscripts c and p), and $k(d_{ij})$ is the transmission kernel based on the inter-farm distance d_{ij} between infectious farm i and susceptible farm j. As described below, c_{mn} and $k(d_{ij})$ were estimated from the 2010 FMD epidemic data.

The local farm-level reproduction number R_i is then calculated as:

$$R_i = \sum_{j \neq i} \left(1 - \exp\left(-r_{ij} T\right)\right)$$

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where j represents all farms in the country except farm i, and T denotes the expected length of the infectious period on a farm [3, 4, 6, 19]. In this study, the infectious period was assumed to be 7 days, from an infectious period of 6 days before detection and 1 day for completion of culling.

The transmission coefficient c_{mn} and transmission kernel $k(d_{ij})$, which were estimated using the 2010 FMD epidemic data after the enforcement of movement restrictions in the previous study [12], were applied in this study. The details of estimation methods are described in the previous study [12]. Briefly, we parameterized the transmission kernel by using the following function:

$$k(d) = k_0 \left(1 + \frac{d}{d_0}\right)^{-\alpha}$$

where k_0, d_0 and α are specific parameters to be estimated for the kernel, k_0 returns the maximum value for $k(d)$ at d=0, and d_0 and α determine the shape of the $k(d)$ curve. We examined other functional forms for the kernel developed in the previous study [12], but the kernel function above provided the most satisfactory fit to the epidemic data. Parameters of the transmission kernel and transmission coefficient were estimated by maximum-likelihood estimation using the epidemic data during the period after the first detection of the disease until the implementation of emergency vaccination [12]. Thus, the parameter values of the transmission kernel used in this study were estimated as r_0=0.58, k_0=0.00074 and α=2.47. When the coefficient for cattle-to-cattle farm transmission (c_{cc}) was 1, the relative transmission coefficient for cattle-to-pig farm transmission (c_{cp}) was 0.77, while those for pig-to-cattle farm (c_{pc}) and pig-to-pig farm (c_{pp}) transmission were 2.45 and 3.01, respectively [12].

After calculating the values of R_i for all farms in the country, these values were averaged over 5 × 5 km squares to visualize the spatial distribution of the risk area. R 3.1.0 (R Development Core Team, 2014) was used for calculation of R_i, and ArcGIS10 (Esri, Redlands, CA, U.S.A.) was used for managing spatial data of farms and creating the risk map.

The median value of the local farm-level reproduction number R_i for 89,826 farms in the country was estimated as 0.17 (5th–95th percentiles: 0.01–1.28), and 93% of all farms showed local farm-level reproduction numbers of less than 1 (Fig. 1). These values are visualized as a risk map of the transmission of FMD in Japan in Fig. 2. This map shows that certain areas are at risk of local dissemination of the disease after virus introduction. Large areas with high transmission risk were identified in the Kyushu region, in the southern part of the country, and the Kanto region, in the eastern part of the country.

The evaluation of the spatial transmission risk of FMD across the country revealed spatial heterogeneity of the transmission risk of FMD. High-risk areas were identified in the Kyushu and Kanto regions. Because these regions are the

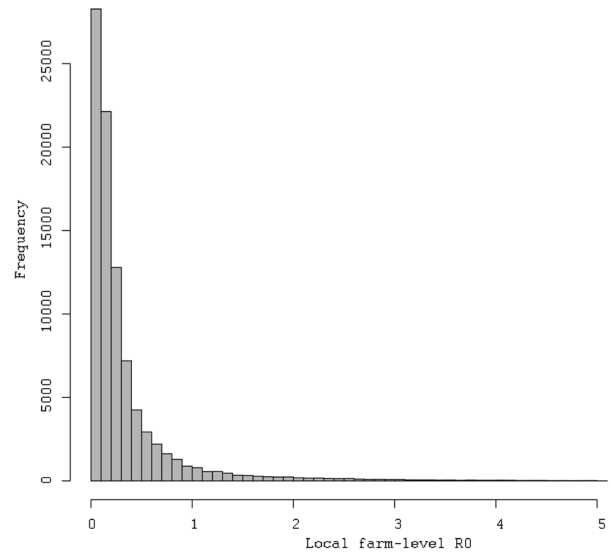

Fig. 1. Distribution of the estimated local farm-level reproduction numbers.

major livestock farming areas with relatively high densities of cattle and pig farms, the results reflect the characteristics of farm distribution and composition of animal species in these regions. FMD is characterized by differences in susceptibility and transmissibility among animal species [1, 7, 8, 18]; FMD-infected pigs excrete a large amount of virus via aerosol, while cattle are highly susceptible to the FMD virus. The transmission coefficient used in this study, which was estimated from the 2010 FMD epidemic, posed a relatively high transmissibility from pig farms [12]. Epidemiological analysis of the 2010 FMD epidemic suggested a significant role of pig farms in the dissemination of the disease during the epidemic [11, 15].

The high-risk areas identified in this study have the potential of spreading the disease under movement restrictions, because the transmission kernel was estimated using the epidemic data during the period from the enforcement of the movement restrictions following the first detection of the disease. Therefore, in such a high-risk area, it is crucial to quickly establish the initial response, including culling and burying animals on infected farms, when an FMD outbreak occurs. However, considering the large epidemic in 2010, which occurred in an area with dense populations of cattle and pigs [14], a culling-only policy could be insufficient to control disease spread, even though the culling policy is the principal approach in the control and eradication of FMD. As was the case in the 2010 epidemic in Japan, difficulties in preventing the spread of the disease in highly dense livestock areas were also reported in previous FMD epidemics in the United Kingdom, the Netherlands and Korea [2, 5, 10, 16, 17]. During these epidemics, because of the rapid and wide spread of the disease, additional control measures, such as emergency vaccination or pre-emptive culling, were required to prevent the disease from disseminating. Therefore, particularly in high-risk areas, it is important to

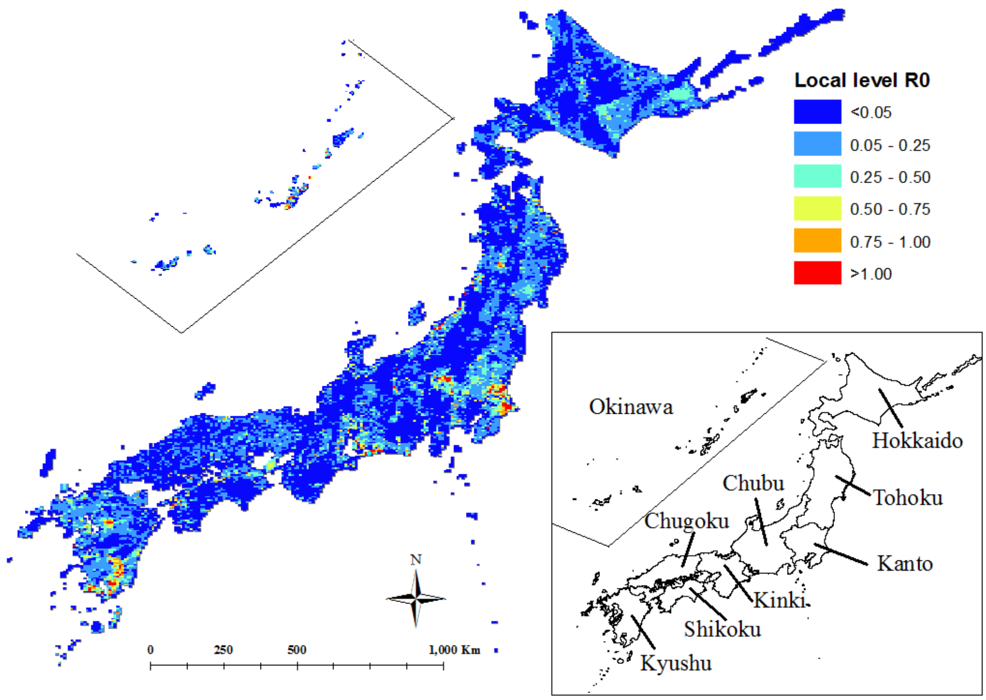

Fig. 2. Risk map of FMD transmission in Japan. The bottom right image shows the regional areas in the country.

prepare additional control measures as well as a prompt culling policy to achieve smooth and efficient containment of an FMD outbreak on a small scale.

In interpreting the results in this study, some points should be noted. First, this study focused on the risk of transmission of the disease after introduction of the FMD virus into the country, not on the risk of introduction of the virus from other countries. There are various possible pathways by which viable infectious agent can be introduced to Japan from other countries, such as illegal import of animals or animal products, or human movement into the country. However, considering the uncertainty in detecting an actual route of introduction, reliable modeling of the geographical risk of introduction appears difficult. Next, the evaluation of the transmission risk was based on the transmission kernel and transmission coefficients estimated from the 2010 FMD epidemic in Japan. The transmission kernel theoretically included all potential routes of disease transmission between farms [6]. However, because of the diversity of FMD viruses, there is a possibility that the virulence or transmissibility of the virus would be different in future epidemics. Moreover, different farm types, such as dairy and beef for cattle farms or breeding and fattening for pig farms, could influence the movement patterns of animals, people and vehicles, as well as farm bio-security. These factors may affect transmission kernels and transmission coefficients, which may need to be adjusted to the conditions of livestock farming areas. Lastly, because of data limitations in the current evaluation, the average number of animals per farm in the prefecture instead of the actual number of animals was applied for 10% of the farms. These approximations may have influenced the output values; in an area where large farms are dominant rather than small or average-size farms, the transmission risk was probably underestimated. We suggest that the estimation of geographical risk needs to be regularly reviewed with updated information for farms. Nevertheless, it is important to evaluate the transmission risk in the country to prepare for future FMD outbreaks by making the best use of data in hand. In this sense, the risk map presented here demonstrates a certain level of the current transmission risk in the country based on data including the farm distribution and animal species as well as the transmission kernel that applied to the large FMD epidemic in 2010.

In this study, the FMD transmission risk map was developed by applying the transmission kernel estimated from the epidemic data. This approach allows us to identify the high-risk areas by calculating transmission potential for all farms in the country. FMD outbreaks still have been reported across the East Asia region [9, 16, 20], so a threat of reintroduction of the FMD virus to Japan remains. This kind of transmission risk map enables decision makers to visually understand the location of high-risk areas and to develop appropriate control strategies in each area. Furthermore, it is useful to raise awareness of the importance of prevention and control of FMD among farmers, relevant stakeholders and societies.

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