Theoretical Epidemiology on Bovine Ephemeral Fever Outbreaks in Tanegashima Island, Kagoshima Prefecture of Japan in 1988

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ABSTRACT. From the end of September to November 1988, a compact scale of bovine ephemeral fever (BEF) outbreaks occurred suddenly in Tanegashima island of Kagoshima Prefecture, southern part of Kyusyu island of Japan. The BEF outbreak pattern showed epidemiological characteristics as follows; (1) outbreak spread from few foci to zone during one month, and (2) the disease might be transmitted in farms with a fixed probability of adequate contact. By using the above aspects, we attempted to analyze the disease theoretically with the application of Poison distribution and Reed-Frost model. The BEF incidence in farms was in well accord with the Poison distribution. As the very rare event occurred in unit time or in unit area in this epidemic, the cattle population at risk were equivalently susceptible to BEF virus in this island, due to the influence of no vaccination to BEF control before the first outbreak. Similarly, the epidemic curve of the Reed-Frost model was proved to fit well the incidence observed in a farm, and the probability of adequate contact was induced as $p=0.226$. If the cattle population is less than 5 in this farm, the outbreak would not occur in the first instance.—KEY WORDS: bovine ephemeral fever, epidemic, Poison distribution, Reed-Frost model.


Bovine ephemeral fever (BEF) has occurred epidemically several times since the epidemic of 1953 in Japan, the most recent outbreak of BEF, took place in throughout Kyusyu island during the fall of 1988 (Statistics on Animal Hygiene, Japan, 1989). From the end of September to November 1988, a compact scale of BEF outbreaks occurred suddenly in Tanegashima island of Kagoshima Prefecture, southern part of Kyusyu island. The BEF outbreak pattern was epidemically characeterized by the followings, (1) outbreak spread from few foci to the zone during one month, and (2) the disease might be transmitted in a farm with a fixed probability of adequate contact.

On the other hand, theoretical epidemiology can be discussed by using mathematical 'models' that attempt to simulate the natural occurrence pattern of a disease [7].

There are a variety of statistical distribution models for the spatial distribution of events. For example, Poison distribution is important for epidemiology because it relates to the spatial and temporal distribution of a disease [7]. Similarly, Reed-Frost model is one of the binomial type distribution models for the disease transmission in population involved in hard immunity [1].

In the present study we attempted to analyze BEF outbreaks in Tanegashima island theoretically with the application of the Poison distribution and the Reed-Frost model.

MATERIALS AND METHODS

Epidemiologic data of BEF: Dairy records of BEF outbreaks in Tanegashima island from September 27 to November 25, 1988 were obtained from a report of Kumage Branch, Kagoshima Chuo Livestock Hygiene Service Center in Kagoshima Prefecture. Other information on the BEF outbreaks in Tanegashima island was summarized from the official outbreak report of Department of Livestock Industry of Kagoshima Prefecture, which included circumstances of the BEF outbreak, clinical findings, virus isolation and serum neutralizing tests, as in the report of Nagasaki Prefecture [2]. BEF was diagnosed according to the direction from the Animal Health Division, Livestock Industry Bureau, Ministry of Agriculture, Forestry and Fisheries (MAFF) namely: (1) cattle showing clinical signs characteristic of BEF (sudden fever up to 41-42°C, anorexia, salivation, cutaneous muscle tremor, lameness and instability standing, etc.), (2) BEF virus isolation from the infected cattle, and (3) an increase in neutralizing antibodies against BEF virus in paired sera of the infected cattle. If criteria (1) and (2) or (1) and (3) were met, the Livestock Hygiene Service Center made the final diagnosis as BEF.
BEF is usually diagnosed from clinical signs and history in an epidemic situation [6]. In the BEF outbreaks of Tanegashima island, the Kumage Branch, Kagoshima Chuo Livestock Hygiene Service Center of Kagoshima Prefecture determined officially 4 cattle according to criteria (1) and (3), and diagnosed subsequently 1,005 cattle according to criteria (1) as BEF. Therefore, a total of 1,009 cattle were used for data analyses as BEF in Tanegashima island.

Meteorologic data: The meteorologic data in Tanegashima island during the BEF outbreaks from October to November, 1988 were received from Tanegashima Meteorological Station in Meteorologic Agency of Japan. The data included temperatures, moistures, wind directions and speeds in each day.

Epidemiologic indices of BEF: Incidence of BEF per cattle was expressed as the number of new cases that occurred in the daily and beef cattle population at risk over the epidemic in Tanegashima island. The incidence rate (%) of BEF per cattle or farm was calculated as follows (the incidence of BEF per cattle or farm / cattle or farm population at risk over the epidemic) × 100.

Since there were no correct data available on cattle or farm population at risk over the epidemic, we used the data from annual statistics of livestock, as of February 1, 1988, provided by the Statistics and Information Department, MAFF of Japan.

Case fatality was expressed as the total number of death and culling in the cattle affected with BEF over the epidemic. Case fatality rate (%) was obtained by the following formula; (the total number of death and culling due to BEF / the number of cattle affected with BEF) × 100.

Incidence distribution by farm or in farm: The data of incidence by farm were collected from the daily BEF outbreak records during the first half of October from the first outbreak at Hase village in Minami District of Tanegashima island, in which BEF outbreak was observed most frequently.

For the simulation of Reed-Frost model, the data of incidence in farm was also collected from the typical farm affected completely with BEF in the same village. In the farm, almost all cattle were infected successively during the period.

Poisson distribution: The Poisson distribution [7] was used as the following formula.

\[ P(\lambda) = \frac{e^{-\lambda} \lambda^{x}}{x!}, \quad x=0, 1, 2, ..., \]

where parameter \( \lambda \) is the expected value of average or variance, and is correspondent to the sample mean (\( \bar{x} \)) with the maximum likelihood method; \( \lambda = \bar{x} \).

Probability of the Poisson distribution is calculated in order as the following formulas.

\[ P(\lambda) = e^{-\lambda}, \quad P(\lambda-1) = \lambda e^{-\lambda} = \lambda P(\lambda), \]

\[ P(\lambda) = \frac{\lambda}{x} P(\lambda=x-1) \quad (x \geq 1). \]

Reed-Frost model: The mathematical formulation of the Reed-Frost model [1, 4] was used as the following.

\[ C_{t+1} = S_{t} (1 - q^{t}) \]

\[ C : \text{the number of cases (clinically diseased individuals)} \]

\[ S : \text{the number of susceptibles} \]

\[ q : \text{the probability of no adequate contact} \]

\[ p = 1 - q : \text{the probability of adequate contact} \]

\[ \text{subscript } t : \text{a time counter}. \]

The above formula was extended as follows.

\[ q = 1 - p = I - K (N - 1) \]

\[ C_{t+1} = S_{t} (1 - q^{t}) \]

\[ C_{t+1} = S_{t} (l - (1 - K (N - 1))^{t}) = S_{t} (1 - e^{(-K (N - 1))^{t}}) \]

\[ S_{t} = S_{0} e^{(-K (N - 1))^{t}} \]

\[ S_{2} = S_{0} e^{(-K (N - 1))^{t}} = S_{0} e^{(-K (N - 1)) (c0 + c1)} \]

\[ S_{m} = S_{0} e^{(-K (N - 1)) c_{m-1}} = S_{0} e^{(-K (N - 1)) c_{m-1} + + + c_{m-1}} \]

\[ c_{0} + c_{1} + + + c_{m-1} = S_{0} - S_{m} \]

\[ S_{0} : \text{the initial number of susceptibles at time 0}. \]

\[ S_{m} : \text{the number of susceptible after time m}. \]

\[ N : \text{the number of population}. \]

\[ K : \text{the number of contact at time interval}. \]

Data analyses: Data analyses for the Reed-Frost model were done as applied in SAS 6.07 (SAS Institute Inc., 1991). Calculation for application of the Poisson distribution was carried out by using a FORTRAN program in the computer library of the MAFF [5], and by the NEC ACOS 930/20 computer in the Tsukuba Computer Center for Agriculture, Forestry and Fisheries Research.

RESULTS

Topography and climate of Tanegashima island: Figure 1 shows the topographical features of Tane-
gashima island. The island (131°E, 30°43'N) is on 50 km south of Kyusu island. The land area is 994.7 km² (65 km length and 156 km width) with lots of soft hills, and consists of three Districts (Nishi, Naka and Minami).

The average temperature varied from 22 to 19°C and the humidity was about 65% over October to November, 1988. We had almost no rain during the period. The average wind velocity recorded at 8 days was over 3.4 m/sec, and northwest or northeast

Fig. 1. Topography of Tanegashima island in Kagoshima Prefecture of Kyusu island, Japan.

Fig. 2. Spread of bovine ephemeral fever outbreak in Tanegashima island from September 27 to November 1st, 1988. ●: One focus of farm outbreak.
wind prevailed in October.

Spread and circumstances of the outbreaks: The time sequence of the spread of BEF in Tanegashima island is showed in Fig. 2. The first outbreak observed in the borderline between Minami and Naka Districts on September 27, 1988, and within few days the initial outbreak foci were recognized along the watershed line from northeast to southwest on a hill of 80 to 190 m high, as shown in the left part of Fig. 2. During October the outbreak zone spread from the original foci over Minami and Naka Districts (the right part of Fig. 2). No outbreaks, however, occurred in Nishi District.

A total number of cattle affected with BEF was 1,009 on 425 farms in Minami and Naka Districts. The incidence rate (%) per cattle was extremely high, and about half of farm population was also affected with BEF in each District, as shown in Table 1.

Table 1. Incidence and case fatality rates of bovine ephemeral fever outbreaks in Tanegashima island of Kagoshima Prefecture, 1988

<table>
<thead>
<tr>
<th>District</th>
<th>Incidence rate (%)</th>
<th>Case fatality rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cattle</td>
<td>Farm</td>
</tr>
<tr>
<td>Nishi</td>
<td></td>
<td>13.4</td>
</tr>
<tr>
<td>Naka</td>
<td>21.2</td>
<td>34.6</td>
</tr>
<tr>
<td>Minami</td>
<td></td>
<td>7.7</td>
</tr>
</tbody>
</table>

Table 2. Incidence distribution of bovine ephemeral fever by farm, during a half month from the first outbreak, in Hase village in Tanegashima island of Kagoshima Prefecture, 1988

<table>
<thead>
<tr>
<th>Incidence (cattle)</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (farm)</td>
<td>86</td>
<td>68</td>
<td>24</td>
<td>11</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Total number of farm: 190. Average (x): 0.811. Variance (x²): 0.863. Variance/Average (x²/x): 1.065.

Fig. 3. Incidence distribution of bovine ephemeral fever by day in Minami District of Tanegashima island from October 1st to November 17, 1988.

The incidence per cattle by day from October to November in Minami District is showed in Fig. 3. The pattern of BEF spread was a negative skewed normal distribution. The incidence tended to be low in the first half of October, and increased later, reaching peaks at the end of October. It terminated by November 17, 1988. The incidence pattern in Naka District was almost similar to that in Minami District (data not shown).

Clinical findings and fatality: Characteristic clinical findings were observed over the epidemic. The cattle showing light symptoms recovered perfectly in two or three days. Severe cases took more few days for recovery, showing instability of difficulty in standing. Lactation ceased completely in daily cows. As shown in Table 1, case fatality rate in the epidemic was about 2% and not different from that of daily and beef cattle.

Fitting of the Poisson distribution: The incidence
Table 3. Fitting of Poisson distribution\(^a\) and goodness-of-fit test

<table>
<thead>
<tr>
<th>Incidence (cattle)</th>
<th>Probability</th>
<th>Number of farms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
<td>Expected</td>
</tr>
<tr>
<td>0</td>
<td>86</td>
<td>84.479</td>
</tr>
<tr>
<td>1</td>
<td>68</td>
<td>68.472</td>
</tr>
<tr>
<td>2</td>
<td>24</td>
<td>27.749</td>
</tr>
<tr>
<td>3</td>
<td>11</td>
<td>7.497</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>1.519</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>0.246</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0.033</td>
</tr>
<tr>
<td>Residue</td>
<td>0</td>
<td>0.0002</td>
</tr>
</tbody>
</table>

\(^a\) \(P(X=x)=e^{0.811}0.811^x/x!\) given \(x=0\) to 6.
[Result of goodness-of-fit test]
 Degrees of freedom: 2, Chi-square value: 1.321<5.99 (p=0.05) \(\text{H}_0\): Accept; Incidence by farm is in accord with the Poisson distribution.

Table 4. Incidence distribution of bovine ephemeral fever in a farm\(^b\), in Hase village of Tanegashima island during October, 1988

<table>
<thead>
<tr>
<th>Date(^b)</th>
<th>Incidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>October 4</td>
<td>1</td>
</tr>
<tr>
<td>October 5</td>
<td>1</td>
</tr>
<tr>
<td>October 14</td>
<td>1</td>
</tr>
<tr>
<td>October 15</td>
<td>4</td>
</tr>
<tr>
<td>October 17</td>
<td>1</td>
</tr>
<tr>
<td>October 18</td>
<td>2</td>
</tr>
<tr>
<td>October 19</td>
<td>0</td>
</tr>
<tr>
<td>October 20</td>
<td>1</td>
</tr>
<tr>
<td>October 23</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>13</td>
</tr>
</tbody>
</table>

\(^a\) Cattle population in the farm=14.
\(^b\) Date of the outbreak.

Table 5. A epidemic curve predicted by the Reed-Frost model\(^c\)

<table>
<thead>
<tr>
<th>Time interval ((t))</th>
<th>Number of susceptibles ((S_t))</th>
<th>Number of cases ((C_t))</th>
<th>Number of immunes ((I_t))</th>
<th>Incidence observed (Duration)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>12</td>
<td>2</td>
<td>—</td>
<td>2 (Oct. 4–9)</td>
</tr>
<tr>
<td>1</td>
<td>7</td>
<td>5</td>
<td>2</td>
<td>5 (Oct. 10–15)</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>5</td>
<td>7</td>
<td>4 (Oct. 16–21)</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1</td>
<td>12</td>
<td>2 (Oct. 22–27)</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>0</td>
<td>13</td>
<td>0 (Oct. 28– )</td>
</tr>
</tbody>
</table>

\(^c\) The formula for the model is: \(C_{t+1}=S_t(1-q^t)\) given \(p=0.226\), \(q=1-p=0.774\).

\(C_1=12(1-0.774^2)=5\); \(S_1=12-5=7\)

\(C_2=7(1-0.774^3)=5\); \(S_2=7-5=2\)

distribution by farm in Hase village is indicated in Table 2. The total number of farm was 190 and the average incidence was 0.811. Probability of the Poisson distribution was calculated by the parameter \(\lambda=(0.811)\). As shown in Table 3, the incidence by farm was well explained by the Poisson distribution.

Simulation of the Reed-Frost model: The farm data for the simulation of the Reed-Frost model are indicated in Table 4. The first outbreak occurred on October 4, and a total of 13 cattle had affected with BEF by October 23 when the outbreak was terminated. We postulated that the number of the initial outbreak was 2 (\(C_0=2\)) on October 4 and 5. Then, the parameters \((N=14, S_0=12 \text{ and } S_m=14-13=1)\) were substituted onto the first formula \(S_m=S_0e^{-K(N-1)/50-5m}\), and \(K=2.937\) was induced. From the second formula \(q=1-p=1-K/(N-1)\), \(p=0.226\) and \(q=0.774\) were calculated. Furthermore, the \(q\) and parameters \((S_t \text{ and } C_t)\) at \(t_0\) were substituted onto the third formula \([C_I=S_0(1-q^t)]\), and as \(t\) varied from 1 to 4 in order, \(C_I\) to \(C_4\) were calculated.

The epidemic curve predicted by the Reed-Frost model is presented in Table 5. In case \(t\) interval (length of time period) was set as 6 days, the incidence observed fitted well with the epidemic curve of the Reed-Frost model.

Discussion

The climate in October in Tanegashima island was moderate (average temperature: 21-19°C, humidity: 65%). The moderate climate was considered to have a major influence upon the epidemic of BEF, since it might be a good condition for the activity of BEF vectors over the epidemic. In addition, no voluntary
vaccination for BEF control would play a dominant role in inducing high incidence rate. Because of these circumstances, the BEF outbreak might spread rapidly from few foci to zone by the end of October in this island, as a result of Fig. 2.

On the other hand, the pattern of BEF outbreak which occurred contemporaneously in the northern part of Kyushu island was clearly different from that in Tanegashima island. Because this epidemic appeared to arise from a point source and at one time, the pattern of incidence by day was a log-normal distribution and the cattle population at risk might expose to the vectors of BEF before the initial outbreak [3]. It may be, therefore, desirable to discuss in this study on the spread pattern after disease invasion rather than on source of the BEF epidemic.

Then we speculated theoretical epidemiology as regards some aspects in the BEF epidemic of Tanegashima island; one was the incidence distribution by farm (Table 2), another was that in cattle population in farm (Table 4), and the outbreak of infection in each population was considered to occur successively in a unit time or unit area.

First the former aspect was applied to the Poisson distribution. The Poisson distribution is concerned with counts. It is found that the events occurred randomly in space or time [7]. The BEF incidence by farm was well in accord with the Poisson distribution with goodness-of-fit test (Table 3), which indicated that the outbreak of BEF occurred randomly in a unit time (during the first half of October from the first outbreak) or a unit area (in Hase village of Tanegashima island) with one parameter, the average incidence in a unit time or a unit area (0.811 cattle).

Since it was rarely the case that the event occurred randomly on a unit area in a unit time, it may be concluded that the cattle population at risk were equivalently susceptible to BEF virus due to no vaccination to BEF control before the first outbreak.

Secondary, we discussed on the BEF incidence distribution (infection and transmission) in farm. The major assumptions in the Reed-Frost model are as follows; (1) infection is spread directly from infected individuals to others by "adequate contact" and in no other way, (2) once contacted, the individual (if susceptible) will develop the disease and be infectious in the next time period, following which it will be immune, and (3) there is a fixed probability of adequate contact between any two individuals [1].

Then, we examined the incidence distribution in farm according to the above assumptions in the Reed-Frost model; (1) the adequate contact meant a virus transmission by vectors, and no instance of direct transmission from cattle to cattle by contact has ever been reported in the epidemic of BEF [6], (2) most of the cattle which developed the clinical symptoms were infectious in 2 to 4 days by viremia, and subsequently recovered within 3 to 4 days from the onset of clinical signs [8], and (3) a no previous data of p; probability of adequate contact in BEF infection have been indicated, we induced p=0.226 for the application of this model.

Moreover, we discussed in detail on the following assumptions; 1) the adequate contact by BEF vectors might be randomly mixed with a good condition for the activity of the vectors in the moderate climate, 2) the sensitivity in the cattle population was homologous to BEF agent, similar to the Poisson distribution, and 3) the condition in the farm remained constant during the epidemic because of no vaccination and disinfection to vector control.

As a result of Table 5, the epidemic curve of the Reed-Frost model was proved to accord well with the incidence observed in the farm. This model was illustrative of the principles that underlay the spread of infectious disease [4].

Furthermore, Martin et al. [1] indicated that if $p \times S$ (number of susceptible) was greater than 1, the epidemic can occur; whereas if $p \times S$ was less than 1, the epidemic would die out or not occur in the first instance. The probability $(p=0.226)$ might be adequate, as continuous infection in farm occurred actually in this scale of cattle population (Fourteen cattle). However, the outbreak would not occur in the first instance $(p \times S$ less than 1), provided that the cattle population has been less than 5 in the farm. As shown in Table 1, about $13-21\%$ (per cattle) and $40-54\%$ (per farm) were really affected with BEF over the epidemic. It should be epidemiologically pointed out that if small holders (less than 5 cattle) did not exceedingly prevail in the farm population, the prevalent BEF outbreaks might occur in spite of disinfection and urgent vaccination for the BEF control by the end of October.

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