Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.
Enhancing an Evidence-Based Decision Making System for Foot-and-Mouth Disease

A thesis presented in partial fulfilment of the requirements for the degree of Doctor of Philosophy at Massey University

Masako Wada
2016

Institute of Veterinary, Animal and Biomedical Sciences
Massey University
Palmerston North, New Zealand
Foot-and-mouth disease (FMD) is a highly contagious disease with significant economic consequences, for which urgent and rational decisions are essential. It is a great concern for countries worldwide where livestock industries are important, regardless of the current FMD status. This thesis addressed the problems in the existing decision support systems used by the current FMD-free countries, with a particular focus on New Zealand.

Because the exact source of infection is uncertain in the spatially and temporally concentrated focus of an FMD epidemic, it is challenging to predict the behaviour of FMD and determine the best control alternatives within a given susceptible population. The studies proposed a new approach for descriptive spatio-temporal analyses of local spread patterns, which was applied to the data from the FMD outbreaks in Cumbria (UK, 2001), Miyazaki (Japan, 2010), and Andong (Republic of Korea, 2010). The analyses identified herd-specific risk factors of local spread: size of a susceptible premises, infectious premises with pigs and susceptible premises with cattle were positively associated with hazard of local spread in all the three epidemics. In addition, the adjusted hazard of local spread varied markedly by outbreak. The UK FMD epidemic in 2001 had the highest hazard of local spread. The findings highlight the needs of care in interpolating the local spread probabilities from one epidemic for use of disease modelling for a different susceptible population.

Detailed investigation of the FMD epidemic in Japan in 2010 illustrated a dynamic change in the patterns of local spread during the epidemic prior to emergency vaccination, suggesting contribution of human activities in addition to purely environmental factors to local spread. A stochastic spatial simulation model, using the local spread parameters derived from the analyses showed a high predictive accuracy, in terms of demographical, temporal and spatial patterns of infection. The model indicated that emergency vaccination played an important role in mitigating potentially unwanted outcomes of an epidemic, such as disease spread outside the prefecture. In addition, the model predicted
that both epidemiological and economic consequences of the epidemic could have been reduced by earlier application of vaccination with a smaller vaccination ring for the epidemic in Japan in 2010.

To enhance contingency planning for FMD, a disease simulation modelling system was developed, by adding an economic module to the existing FMD simulation model for New Zealand. The modelling system allowed estimation of the direct and macroeconomic costs of a simulated FMD epidemic. Analyses of data generated by the disease simulation modelling system indicated that vaccinate-to-die was economically preferred to stamping-out alone or vaccinate-to-live, for a simulated FMD epidemic in the Auckland Region with local spread potential similar to that of the Cumbria outbreak in 2001, which had a high potential of developing into a large epidemic, indicated by a high density of premises, a high cumulative number of IPs, or a high estimated dissemination rate, and local spread patterns similar to Cumbria outbreak (2001). Vaccinate-to-live was economically suboptimal under the current OIE standard regarding recovery of FMD-free status. The results were robust to the uncertainty in the resource capacity, vaccination effectiveness, and the early scale of an epidemic, but sensitive to the choice of vaccination radius. VTL was always economically suboptimal under the current OIE code, but would be advantageous if the OIE’s waiting period was shortened by 3 months. Using more refined parameters, future work is required to investigate other potentially more advantageous options, such as vaccination applied to specific species or in alternative prioritisation.

The studies presented in this thesis demonstrated that simulation models that incorporated the current best epidemiological and economic knowledge might enhance contingency planning and decision making for the management of FMD. Simulation models could also be used as the quantitative basis of communication with decision makers and stakeholders, which would then encourage informed discussion around disease control measures.
Acknowledgements

I sincerely thank my three supervisors, Tim Carpenter, Mark Stevenson, and Naomi Cogger, who generously shared their knowledge and expertise, and guided me throughout the thesis. I was very fortunate to have two chief supervisors, Tim and Mark. Thank you Tim, for patiently mentoring me and giving a guide to good research practice. Thank you Mark, for welcoming me to the team EpiCentre, and giving me a challenging topic that helped me learn a lot of things. Thank you Naomi, for always giving me nice suggestions and being supportive. Special thanks to Roger Morris, who generously supported my later PhD life and gave me insightful comments, in return for me travelling and assisting his work abroad which I enjoyed. Thanks go to the three examiners, Nigel French (Massey University), Graeme Garner (University of Sydney) and Andres Perez (University of Minnesota) whose peer review contributed to improving the thesis.

Many thanks to Shirley Morris, Fiona McNish, and Julia Rayner at Massey Graduate Research School for their assistance and provision of the Massey University Doctoral Scholarship. Many thanks to Shigeo Ito, Chihiro Sugimoto, Kazuhiko Ohashi, and Takashi Umemura, the committee of Japan Society for the Promotion of Science International Training Program for young scientists at Graduate School of Veterinary Medicine, Hokkaido University, for provisions of this opportunity to come to Massey University and study epidemiology. Thanks to Kevin Stafford, Wendi Roe, and Debbie Hill at the IVABS for their kind assistance.

My thanks go as well to Andre van Halderen, Rod Forbes, Bex Ansell, Paul Bingham, Katie Hickey, Katie Owen, Tom Rawdon, Daan Vink and Mary van Andel at the Ministry for Primary Industries for generously sharing information regarding New Zealand’s preparedness for FMD. Thanks to Ashley Lienert at the Reserve Bank for his introduction to macroeconomics. Thanks to Robert Sanson for generously sharing his work on modelling FMD. Thanks to Mutsuyo Kadohira at Obihiro University of Agriculture and Veterinary Medicine, Japan Agricultural Cooperatives (JA) Koyu and Osuzu, UK Department of Environment, Food and Rural Affairs and Korean Animal
and Plant Quarantine Agency for provision of the data. Thanks to Martin Hazelton for his valuable statistical advice. Thanks to Amy Hagerman at the United States Department of Agriculture for sharing her expertise in disease macroeconomics. Thanks to Bryan O’Leary, Masood Sujau and Mark Stern for development and maintenance of InterSpread Plus. My special thanks go to Simon Verschaffelt for his general help throughout my PhD.

Thanks to all the EpiCentre staff and fellow students, including (but not limited to) Nelly Marquetoux, Milan Gautam, Juan Sanhueza, Alicia Coupe, Katja Isaksen, Arata Hidano, Kandarp Patel, Emilie Vallee, Ben Phiri, Carolyn Gates, Chris Compton, Christine Cunningham, Cord Heuer, Karyn Froud, Wendy Maharey, Ahmed Fayez, Jackie Benschop, Eutteum Kim, Jun Hee Han, Long van Nguyen, Raymond Hamoonga, Anou Dreyfus, Sarah Rosanowski, and Lesley Stringer, for friendly discussions and sharing tips about epidemiology, modelling, writing, R coding, and general help. Special thanks to Nelly, Juan and Emilie, who stood by my side whenever I needed it.

To my parents Toshiyuki and Sumiko Wada, and all my family, who I may not have been in touch with as closely as I wanted, thank you for your patience, encouragement and understanding. Very special thanks to Ilyas for always cheering me up, and helping me take things easy when I was under pressure.
List of Publications


List of Presentations

2015


2014


2012


2011

Wada, M., Stevenson, M. and Morris, R.S.: The principles of farm-level economic decision making. Oral presentation at New Zealand Veterinary Association annual conference Epidemiology and Animal Health Management, Jun 2011, Hamilton, New Zealand
Table of Contents

Abstract................................................................................................................................. i
Acknowledgements ........................................................................................................... iii
List of Publications ........................................................................................................... v
List of Presentations ......................................................................................................... vi
Table of Contents .............................................................................................................. vii
List of Figures ................................................................................................................... xii
List of Tables .................................................................................................................... xvii
Abbreviations ................................................................................................................... xix
1. Introduction .................................................................................................................. 1
2. Literature Review ....................................................................................................... 3
   2.1. Introduction ........................................................................................................... 3
   2.2. Epidemiology of FMD ....................................................................................... 4
       2.2.1. Aetiology ....................................................................................................... 4
       2.2.2. Global distribution of FMD virus ............................................................... 5
       2.2.3. Host range .................................................................................................... 6
       2.2.4. Clinical aspects ............................................................................................ 7
       2.2.5. Transmission mechanisms ........................................................................ 7
       2.2.6. Control measures ........................................................................................ 8
   2.3. Infectious disease spread modelling for FMD ..................................................... 10
       2.3.1. Types of FMD simulation models .............................................................. 11
       2.3.2. Estimation of local spread ......................................................................... 12
       2.3.3. InterSpread Plus models .......................................................................... 14
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3.4. Davis Animal Disease Simulation (DADS) models</td>
<td>17</td>
</tr>
<tr>
<td>2.3.5. The North American Animal Disease Model (NAADSM)</td>
<td>18</td>
</tr>
<tr>
<td>2.3.6. AusSpread models</td>
<td>19</td>
</tr>
<tr>
<td>2.4. Economic aspects of disease control</td>
<td>20</td>
</tr>
<tr>
<td>2.4.1. Evaluation criteria</td>
<td>22</td>
</tr>
<tr>
<td>2.4.2. Production losses</td>
<td>23</td>
</tr>
<tr>
<td>2.4.3. Export loss</td>
<td>25</td>
</tr>
<tr>
<td>2.4.4. Secondary impacts</td>
<td>26</td>
</tr>
<tr>
<td>2.4.5. Intervention costs</td>
<td>27</td>
</tr>
<tr>
<td>2.4.6. Externalities</td>
<td>29</td>
</tr>
<tr>
<td>2.5. Conclusion</td>
<td>30</td>
</tr>
<tr>
<td>2.6. References</td>
<td>31</td>
</tr>
<tr>
<td>3. Estimation of the hazard of local spread for foot-and-mouth disease</td>
<td>41</td>
</tr>
<tr>
<td>3.1. Abstract</td>
<td>41</td>
</tr>
<tr>
<td>3.2. Introduction</td>
<td>42</td>
</tr>
<tr>
<td>3.3. Materials and methods</td>
<td>44</td>
</tr>
<tr>
<td>3.3.1. Epidemic data</td>
<td>44</td>
</tr>
<tr>
<td>3.3.2. Creation of survival dataset</td>
<td>48</td>
</tr>
<tr>
<td>3.3.3. Survival analyses</td>
<td>51</td>
</tr>
<tr>
<td>3.4. Results</td>
<td>52</td>
</tr>
<tr>
<td>3.4.1. Descriptive statistics</td>
<td>52</td>
</tr>
<tr>
<td>3.4.2. Crude model (typical premises)</td>
<td>54</td>
</tr>
<tr>
<td>3.4.3. Adjusted model (adjusted for species and size)</td>
<td>56</td>
</tr>
<tr>
<td>3.5. Discussion</td>
<td>59</td>
</tr>
<tr>
<td>3.6. Conclusion</td>
<td>63</td>
</tr>
<tr>
<td>3.7. Acknowledgements</td>
<td>63</td>
</tr>
<tr>
<td>3.8. References</td>
<td>63</td>
</tr>
</tbody>
</table>
   4.1. Abstract ..................................................................................................................... 67
   4.2. Introduction .............................................................................................................. 68
   4.3. Materials and methods ............................................................................................ 71
      4.3.1. Data .................................................................................................................. 71
      4.3.2. Epidemiological phases .................................................................................... 73
      4.3.3. Parametric survival modelling ...................................................................... 74
      4.3.4. Parameters of the simulation model .............................................................. 74
      4.3.5. Evaluation of alternative control scenarios .................................................. 76
   4.4. Results ..................................................................................................................... 76
      4.4.1. Epidemiological phases .................................................................................... 76
      4.4.2. Hazard of FMD transmission ...................................................................... 78
      4.4.3. Simulation model ............................................................................................. 80
      4.4.4. Evaluation of alternative control scenarios .................................................. 86
   4.5. Discussion ............................................................................................................... 89
   4.6. Conclusion .............................................................................................................. 91
   4.7. Acknowledgements ............................................................................................... 92
   4.8. References ............................................................................................................. 92
5. Development of an economic module for a foot-and-mouth disease epidemic in New Zealand ................................................................. 95
   5.1. Abstract .................................................................................................................. 95
   5.2. Introduction ............................................................................................................ 96
   5.3. Materials and methods ........................................................................................... 98
      5.3.1. Overview .......................................................................................................... 98
      5.3.2. Simulation of an FMD epidemic (Auckland incursion) ................................... 99
      5.3.3. Estimation of the direct costs ........................................................................... 103
      5.3.4. Estimation of the macroeconomic costs ......................................................... 105
List of Figures

Figure 3-1 Location and infection status of all foot-and-mouth disease (FMD) susceptible livestock premises within the study area (blue triangle: primary case, red: infected, grey: uninfected) for the FMD outbreaks in Cumbria (UK, 2001), Miyazaki (Japan, 2010), and Andong (Republic of Korea, 2010). .......................................................... 47

Figure 3-2 Survival function and instantaneous hazard estimated by Kaplan-Meier method (and 95% confidence intervals shown in shade) for local spread infection of foot-and-mouth disease (FMD) since the onset of infectiousness in the potential source premises for the FMD outbreaks in Cumbria (UK, 2001), Miyazaki (Japan, 2010), and Andong (Republic of Korea, 2010). ...................................................................... 53

Figure 3-3 Contour plots (top) and perspective plots (bottom) of the predicted daily hazard of local spread of foot-and-mouth disease (FMD) as a function of distance from the potential source premises and the number of days elapsed since the onset of infectiousness for the FMD outbreaks in Cumbria (UK, 2001), Miyazaki (Japan, 2010), and Andong (Republic of Korea, 2010). ............................................. 55

Figure 3-4 Predicted adjusted daily hazard of local spread of foot-and-mouth disease (FMD) on the first day of infectiousness for the FMD outbreak in Cumbria (UK, 2001), Miyazaki (Japan, 2010) and Andong (Republic of Korea, 2010). ................................................... 58

Figure 4-1 A map of Japan [top] and Kyushu Island [bottom], showing the location of the investigated area (in green), where a foot-and-mouth disease (FMD) outbreak occurred in 2010.............................................................................................................. 72

Figure 4-2 Estimated hazard ratio (HR) (points) and 95% confidence intervals (whiskers) of local spread of foot-and-mouth disease (FMD) for seven phases (silent spread phase, and weeks 1, 2, 3, 5, 6, and 7) relative to week 4, i.e., a week prior to application of vaccination (HR = 1: dashed line), for the FMD epidemic in Japan (2010). .............................................................................................................................. 77

Figure 4-3 Probabilities of local spread of foot-and-mouth disease (FMD) by phase (see section 4.4.1) used in the simulation models for the FMD epidemic in Japan (2010). Four types of susceptible premises (species: cattle or pigs and herd size: n
= 10 or 100) on day 1 (straight line) and 7 (dotted line) of infectiousness, are presented..........................................................................................................................82

Figure 4-4 Cumulative number of infected premises (IPs) for the actual and simulated epidemics (median and the 5th and 95th percentiles of 100 iterations) for the foot-and-mouth disease (FMD) epidemic in Japan (2010)...........................................................83

Figure 4-5 Distribution of herd size [A] and proportion of premises by dominant species on premises [B] for the total population, and actual and simulated infected premises (IPs) (median, 5th and 95th percentiles of 100 iterations) for the foot-and-mouth disease (FMD) epidemic in Japan (2010). ........................................................................84

Figure 4-6 Kernel density (bandwidth = 1.00 km) of new cases by phase (see 4.4.1) for the actual and simulated epidemics (median, 5th and 95th percentiles of 100 iterations) for the foot-and-mouth disease (FMD) epidemic in Japan (2010). The asterisk (*) shows the primary case. ..................................................................................................85

Figure 4-7 Box and whisker plots showing the ratios of the simulated outcomes of an epidemic for the number of infected premises (IPs, reference: 280 IPs), the number of culled (infected or vaccinated) premises (880 premises), epidemic duration (57 days), culling duration (76 days) and the size of the infected area (187 km²) to the actual values (in parenthesis) for the five control strategies (5w10k, 5w3k, 3w10k, 3w3k and novac: 10 km vaccination in week 5, 3 km vaccination in week 5, 10 km vaccination in week 3, 3 km vaccination in week 3 and no vaccination) for the foot-and-mouth disease (FMD) epidemic in Japan (2010). The box, whisker, and dot represent the interquartile range (IQR), 5th and 95th percentile, and outliers, respectively. ............................................................................87

Figure 4-8 Kernel density (bandwidth = 1.00 km) of simulated cases (median, 5th and 95th percentiles of 100 iterations), infected after 21 days onwards since the first confirmation of disease, controlled by the actual (5w10k: 10 km vaccination in week 5) and four alternative strategies (5w3k: 3 km vaccination in week 5, 3w10k: 10 km vaccination in week 3, 3w3k: 3 km vaccination in week 3, novac: no vaccination) for the foot-and-mouth disease (FMD) epidemic in Japan (2010)....88

Figure 5-1 [Left] Map of New Zealand, showing the kernel smoothed density of livestock premises (bandwidth = 5.0 km). [B] Enlarged map of Auckland showing the kernel smoothed density of simulated IPs (median and the 5th and the 95th percentiles of 100 iterations, bandwidth = 5.0 km) and the location of the primary case (*).............................................................................................................................102
Figure 5-2 Median and the 5th and the 95th percentiles of the estimated number of premises where disease was detected, under processing, depopulated, empty (animals were absent), under movement restriction, and inspected, by time from the first detection for simulated foot-and-mouth disease (FMD) epidemics in Auckland, New Zealand (100 iterations)................................. 107

Figure 5-3 Median and the 5th and the 95th percentiles of the estimated amount of selected resources for calculation of the direct costs (variable costs of operation), for simulated foot-and-mouth disease (FMD) epidemics in Auckland, New Zealand (100 iterations)............................................................................................................... 108

Figure 6-1 Kernel smoothed density of livestock premises (bandwidth = 5.0 km) susceptible to foot-and-mouth disease (FMD), and the location of Auckland (pink) and Otago (blue) regions, in which hypothetical primary cases were selected for FMD simulation...................................................................................................... 126

Figure 6-2 Cumulative epidemic curves with a crude estimated dissemination rate ($EDR'$) greater than 1 [left] and smaller than 1 [right], representing a growing epidemic and a diminishing epidemic. $EDR'$ is calculated as the slope of line between days 14 and 21 (blue) divided by that of days 0 and 14 (orange)................................. 130

Figure 6-3 Cumulative distribution functions of the [A] total number of infected premises (IPs), [B] time till eradication, [C] direct costs and [D] macroeconomic costs for simulated foot-and-mouth disease (FMD) epidemics lasting for \( \geq 21 \) days in the high and low density regions in New Zealand, controlled by stamping-out (SO), vaccinate-to-die (VTD), vaccinate-to-live (VTL), and vaccinate-to-live with 3 month waiting period (VTL*) (1,013 and 822 iterations for high and low density regions)........................................................................................................................... 133

Figure 6-4 Variability in the estimated median values, measured by upper/lower 95% confidence limits minus median, for varying sizes of bootstrap samples, for simulated four outcome variables: reduction in the total number of infected premises (IPs) [A], time to eradication [B], direct costs [C] and macroeconomic costs [D] by region (high/low density) and control policy (vaccinate-to-die: VTD and vaccinate-to-live: VTL and VTL*)................................................................................. 136

Figure 6-5 Effectiveness of vaccination policy (3-km ring vaccination starting on day 21 after detection of the primary case) in reduction of the total number of IPs [A] and time to eradication [B], presented as bootstrap median values (points) with their 95% CI (shade) by the region of incursion ($region$), estimated dissemination
rate $\leq 1$ or $> 1$ ($EDR$) and the lower limits of the quantiles of the cumulative number of infected premises (IPs) on day 14 ($qCIP$) for simulated foot-and-mouth disease (FMD) epidemics lasting for $\geq 21$ days in New Zealand ($n = 42 - 113$).

Figure 6-6 Effectiveness of vaccination policy (vaccinate-to-die: VTD and vaccinate-to-live: VTL/VTL*, both applied within 3 km on day 21 onwards after detection of the primary case) in reduction of the direct costs, presented as bootstrap median values (points) with their 95% CI (shade) by the region of incursion ($region$), estimated dissemination rate $\leq 1$ or $> 1$ ($EDR$) and the lower limits of the quantiles of the cumulative number of infected premises (IPs) on day 14 ($qCIP$) for simulated foot-and-mouth disease (FMD) epidemics lasting for $\geq 21$ days in New Zealand ($n = 42 - 113$).

Figure 6-7 Effectiveness of vaccination policy (vaccinate-to-die: VTD and vaccinate-to-live with or without an additional 3-month waiting period: VTL/VTL*, all applied within 3 km on day 21 onwards after detection of the primary case) in reduction of the macroeconomic costs, presented as bootstrap median values (points) with their 95% CI (shade) by the region of incursion ($region$), estimated dissemination rate $\leq 1$ or $> 1$ ($EDR$) and the lower limits of the quantiles of the cumulative number of infected premises (IPs) on day 14 ($qCIP$) for simulated foot-and-mouth disease (FMD) epidemics lasting for $\geq 21$ days in New Zealand ($n = 42 - 113$).

Figure 7-1 Cumulative distribution functions of the [A] total number of infected premises (IPs), [B] time till eradication, [C] direct costs and [D] macroeconomic costs for simulated foot-and-mouth disease (FMD) epidemics lasting for $\geq 21$ days in the Auckland Region, controlled by stamping-out (SO), vaccinate-to-die (VTD), vaccinate-to-live (VTL), and vaccinate-to-live with a 3-month waiting period (VTL*) ($n = 13,459$).

Figure 7-2 Partial rank correlation coefficients (PRCC) for varied explanatory variables: vaccination radius ($radius$, $1 - 20$ km), resource capacity ($resource$, $100 - 500$ premises/day), effectiveness of vaccination ($effectiveness$, $75\% - 100\%$), cumulative number of IPs ($CIP$) and estimated dissemination rate ($EDR$) for four outcome variables for 21"-day start vaccinate-to-die (VTD), vaccinate-to-live (VTL), and vaccinate-to-live with a 3-month waiting period (VTL*) for control of a simulated foot-and-mouth (FMD) disease epidemic in Auckland Region ($n = 13,459$).

Figure 7-3 Predicted net present values (NPVs) of simulated foot-and-mouth disease (FMD) epidemics in the Auckland Region controlled by vaccinate-to-die (VTD),
vaccinate-to-live (VTL), and VTL of a shortened waiting period (VTL*) relative to stamping-out alone, with varying vaccination radii, adjusted for resource capacity, effectiveness of vaccination, cumulative number of IPs (CIP) and estimated dissemination rate (EDR). .......................................................................................................................... 163

Figure 7-4 Optimal vaccination radius that minimised the predicted NPVs of vaccinate-to-die (VTD), vaccinate-to-live (VTL), and VTL of a shortened waiting period (VTL*) relative to stamping-out alone, while resource capacity [A], effectiveness of vaccination [B], cumulative number of IPs (CIP) [C] and estimated dissemination rate (EDR) [D] were varied to the quantiles of the designed or simulated values, for a simulated foot-and-mouth disease (FMD) epidemics in the Auckland Region. .................................................................................................................................... 164
List of Tables

Table 2-1 Economic studies for assessment of alternative strategies for control and eradication of foot-and-mouth disease (FMD) in FMD-free countries ...............28

Table 3-1 Geographical features of the three areas investigated for foot-and-mouth disease (FMD) outbreaks in Cumbria (UK, 2001), Miyazaki (Japan, 2010), and Andong (Republic of Korea, 2010).................................................................46

Table 3-2 An example survival dataset, observing 4 pairs of susceptible premises 1 and infectious premises 2 - 5 (observations 1 – 4)...........................................................50

Table 3-3 Estimated hazard ratio (and 95% confidence interval) for local spread infection of foot-and-mouth disease (FMD) for the crude Weibull regression model for FMD outbreaks in Cumbria (UK, 2001), Miyazaki (Japan, 2010), and Andong (Republic of Korea, 2010).............................................................................................54

Table 3-4 Estimated hazard ratio (and 95% confidence interval) for local spread infection of foot-and-mouth disease (FMD) for the adjusted Weibull regression model for FMD outbreaks in Cumbria (UK, 2001), Miyazaki (Japan, 2010), and Andong (Republic of Korea, 2010).............................................................................................57

Table 4-1 The weekly counts and daily rates of detected and depopulated premises during the course of a foot-and-mouth disease (FMD) epidemic in Miyazaki, Japan in 2010. ..................................................................................................................................73

Table 4-2 Estimated hazard ratio and 95% confidence intervals (in parenthesis) for the full Weibull regression model for local spread infection for a foot-and-mouth disease (FMD) epidemic in Japan (2010) (n = 202,622).........................................................79

Table 4-3 Estimated epidemiological parameters for an InterSpread Plus simulation model for the foot-and-mouth disease (FMD) epidemic in Miyazaki, Japan, in 2010. .....81

Table 5-1 Percentiles of the estimated direct costs and macroeconomic costs and their uncertain ranges for simulated foot-and-mouth disease (FMD) epidemics in Auckland, New Zealand (100 iterations).........................................................................................108

Table 7-1 The median and the 5th and 95th percentiles (in parenthesis) of simulated foot-and-mouth disease (FMD) epidemics lasting for >21 days in the Auckland Region,
controlled by stamping-out only (SO), vaccinate-to-die (VTD), vaccinate-to-live (VTL), and VTL with a hypothetical 3-month waiting period for recognition of FMD-free status (VTL*) (13,459 iterations).
# Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIP</td>
<td>Cumulative number of infected premises</td>
</tr>
<tr>
<td>DEFRA</td>
<td>Department for Environment, Food &amp; Rural Affairs</td>
</tr>
<tr>
<td>DIVA</td>
<td>Differentiating infected from vaccinated animals</td>
</tr>
<tr>
<td>EDR</td>
<td>Estimated dissemination rate</td>
</tr>
<tr>
<td>FAO</td>
<td>Food and Agriculture Organization of the United Nations</td>
</tr>
<tr>
<td>FMD</td>
<td>Foot-and-mouth disease</td>
</tr>
<tr>
<td>FMDV</td>
<td>Foot-and-mouth disease virus</td>
</tr>
<tr>
<td>GAM</td>
<td>Generalised additive model</td>
</tr>
<tr>
<td>GDP</td>
<td>Gross domestic product</td>
</tr>
<tr>
<td>IP</td>
<td>Infected premises</td>
</tr>
<tr>
<td>JA</td>
<td>Japan Agricultural Cooperatives</td>
</tr>
<tr>
<td>MPI</td>
<td>Ministry for Primary Industries, New Zealand</td>
</tr>
<tr>
<td>NPV</td>
<td>Net present value</td>
</tr>
<tr>
<td>NSP</td>
<td>Non-structural protein</td>
</tr>
<tr>
<td>OIE</td>
<td>The Office International des Epizooties</td>
</tr>
<tr>
<td>RNA</td>
<td>Ribonucleic acid</td>
</tr>
<tr>
<td>PRCC</td>
<td>Partial rank correlation coefficient</td>
</tr>
<tr>
<td>SAT</td>
<td>South African Territories</td>
</tr>
<tr>
<td>SO</td>
<td>Stamping-out alone</td>
</tr>
<tr>
<td>SP</td>
<td>Structural protein</td>
</tr>
<tr>
<td>VP</td>
<td>Viral protein</td>
</tr>
<tr>
<td>VTD</td>
<td>Vaccinate-to-die</td>
</tr>
<tr>
<td>VTL</td>
<td>Vaccinate-to-live</td>
</tr>
</tbody>
</table>