

Modelling the spatiotemporal spread and control of viral disease in livestock using a hybrid equation-based and agent-based approach

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Abstract

This thesis presents the Australian Animal DISease (AADIS) model - a new disease modelling approach to support emergency livestock disease preparedness and planning in Australia. AADIS expands the livestock disease modelling capabilities of the Australian Government Department of Agriculture and Water Resources from regional to national-scale. The test case disease for AADIS is foot-and-mouth disease (FMD), which is well-known for its contagiousness and economic importance. A recent study found that a multi-state incursion of FMD has the potential to impact the Australian economy by up to \$52 billion AUD. Modelling the spread and control of FMD is complex as the virus has multiple serotypes, and spreads via multiple pathways to multiple host species. The environment of a potential outbreak is also complex as there is considerable heterogeneity in Australian livestock production systems, market systems, geography and climate, and over 107 million FMD-susceptible commercial animals across approximately 7.7 million km². Further, the responsibility for control and eradication of FMD is spread across seven state/territory jurisdictions.

AADIS addresses the complexities and computational demands of modelling FMD on a national scale with an innovative hybrid model architecture that combines equation-based modelling with agent-based modelling. Implementation highlights include a novel concurrent software architecture, a grid-based spatial-indexing system, an in-memory database, and dynamic outbreak visualisation. Computational efficiencies achieved by AADIS allow complex national-scale stochastic simulations of disease spread and control to be conducted on a standard desktop computer. Benchmark tests against the Australian regional FMD model AusSpread show that AADIS is on average over 400 times faster at regional-scale simulations. For example, AusSpread completes 100 runs of a 21-day disease spread scenario in Victoria in approximately 3 hours. AADIS completes 100 runs of the same scenario in about 30 seconds.

The AADIS hybrid model architecture comprises a deterministic equation-based model (EBM) of disease spread within a herd, and a stochastic, spatially-explicit

agent-based model (ABM) of disease spread between herds, and of disease control. Each herd agent has a customised EBM that provides concise and computationally efficient predictions of the herd infected prevalence and clinical prevalence over time. The ABM consists of lightweight herd agents and a novel active concurrent environment that captures the complex, heterogeneous and irregular nature of an FMD outbreak. The AADIS grid-based spatial-indexing system provides an eight-fold increase in mean spatial query response time over the standard PostgreSQL/PostGIS 'R-Tree-over-GiST' spatial-indexing. This in turn yields a two to three-fold improvement in the overall time taken to run a typical disease spread and control simulation. AADIS provides dynamic graphical visualisation of an outbreak that contrasts a disease manager's limited perception of an outbreak with the physical reality of infected herds in the population. AADIS thus has potential as not only a predictive tool that informs emergency livestock disease preparedness and planning, but also as a vivid training tool for disease managers.

A comprehensive verification and validation program was undertaken to ensure that AADIS is fit for the purpose of supporting FMD policy and response. This included unit and module testing, comparisons with the well-tested and characterised AusSpread and New Zealand InterSpread Plus models, a sensitivity analysis, and an independent review of model features and outputs.

AADIS significantly advances the epidemiological modelling capabilities of the Australian Government Department of Agriculture and Water Resources. It has already been used as a training tool in a United Nations FMD modelling workshop in Rome, and is currently being used in a joint Australia-New Zealand study on improving decision-making in emergency animal disease outbreaks, funded by the Australian Centre of Excellence for Biosecurity Risk Analysis.

Declaration

I certify that the substance of this thesis has not already been submitted for any degree and is not currently being submitted for other degree or qualification.

I certify that any help received in preparing this thesis and all sources used have been acknowledged in this thesis.

[REDACTED] 5 June 2015

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Contributions

The AADIS model architecture, software architecture and implementation comprising over 28,000 lines of Java code, are all original work.

The epidemiological aspects of AADIS evolved collaboratively with Dr Graeme Garner, Dr Sharon Roche and Dr Iain East of the Department of Agriculture and Water Resources, through numerous phone/Skype™ discussions and workshops between 2012 and 2014.

Dr Sharon Roche and Dr Graeme Garner provided the test herd population dataset and test model parameterisation.

Dr Graeme Garner and Dr Sharon Roche ran the AusSpread simulations for the Section 5.2 comparison with AADIS.

Dr Robert Sanson of AsureQuality Limited New Zealand ran the InterSpread Plus simulations for the Section 5.3 comparison with AADIS (as part of CEBRA, 2014).

Dr Iain East of the Department of Agriculture and Water Resources assisted with the statistical analysis of model outputs in the Section 5.1 verification of grid-based spatial-indexing (as part of Bradhurst et al., 2015b), and the statistical analysis of model outputs in the Section 6.1 case study on control strategies (as part of Bradhurst et al., 2015a).

Associate Professor Paul Kwan of the University of New England and former supervisor Professor ASM Sajeev provided strategic guidance for the project and overall supervision of the PhD candidature.

Professor Mark Stevenson of the University of Melbourne conducted the independent assessment of AADIS described in Section 5.6.

Peer-reviewed publications

- Bradhurst R.A., Roche S.E., Garner M.G., Sajeev A.S.M. and Kwan P. (2013). Modelling the spread of livestock disease on a national scale: the case for a hybrid approach. *Proceedings of the 20th International Congress on Modelling and Simulation (MODSIM2013)*, Modelling and Simulation Society of Australia and New Zealand, Adelaide, Australia, December 2013, 345–351. www.mssanz.org.au/modsim2013/A6/bradhurst.pdf
- Bradhurst R.A., Roche S.E., East I.J., Kwan P. and Garner M.G. (2015a). A hybrid modelling approach to simulating foot-and-mouth disease outbreaks in Australian livestock. *Frontiers in Environmental Science*, 3(17). [doi:10.3389/fenvs.2015.00017](https://doi.org/10.3389/fenvs.2015.00017)
- Bradhurst R.A., Roche S.E., East I.J., Kwan P. and Garner M.G. (2015b). Improving the computational efficiency of an agent-based spatiotemporal model of livestock disease spread and control. *Journal of Environmental Modelling and Software*, 77, 1-12. [doi:10.1016/j.envsoft.2015.11.015](https://doi.org/10.1016/j.envsoft.2015.11.015)

Related articles, presentations and press releases

- Bradhurst R.A., Roche S.E. and Garner M.G. (2013). Simulating the spread of animal diseases in Australia using a hybrid modelling approach. *Proceedings of the 2013 Australian and New Zealand College of Veterinary Scientists Science Week Scientific Conference, Epidemiology Chapter*, Gold Coast, Australia, 11-13 July 2013.
- Roche S.E., Bradhurst R.A. and Garner M.G. (2014). Modelling the spread of foot-and-mouth disease across Australia: the case for a hybrid approach. *Proceedings of the 2014 Australian and New Zealand College of Veterinary*

Scientists Science Week Scientific Conference, Epidemiology Chapter, Gold Coast, Australia, 10-12 July 2014.

- Roche S.E., Bradhurst R.A. and Garner M.G. (2014). Overview of the AADIS epidemiological model. Centre of Excellence for Biosecurity Risk Analysis (CEBRA) workshop: Decision support tools for animal disease preparedness, Crawford School of Public Policy, Australian National University, Canberra, Australia, 3–5 September 2014.
- Roche S.E. and Bradhurst R.A. (2014). To vaccinate or not to vaccinate: using modelling to evaluate FMD control options. European Commission for the Control of Foot-and-Mouth Disease (EuFMD), Modelling workshop, Frascati, Italy, 29 Sept – 3 Oct 2014.
- Vallis R. (2014). Australian livestock disease modelling upgrades to 'multi-lane highway'. *Australian Veterinary Journal*, 92(7), 10.
<http://www.ava.com.au/13237>
- Department of Agriculture and Water Resources (2015). Foot and Mouth Disease Modelling Projects – National models. Australian Government, Department of Agriculture and Water Resources, Canberra, ACT, Australia.
<http://www.agriculture.gov.au/animal/health/modelling/fmd>
- University of New England (2015). Livestock disease model to revolutionise response. University of New England, Armidale, NSW, Australia.
<http://blog.une.edu.au/news/2015/02/27/livestock-disease-model-to-revolutionise-response/>
- Garner M.G. (2015). Decision making during each phase of an FMD outbreak response. D.C. Blood Oration and Foot-and-Mouth Disease Workshop, Faculty of Veterinary and Agricultural Sciences, University of Melbourne, VIC, Australia, 5 February 2015.

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