INCORPORATING HETEROGENEITY IN FARMER DISEASE CONTROL BEHAVIOUR INTO A LIVESTOCK DISEASE TRANSMISSION MODEL

Ed Hill
Civic Health Innovation Labs (CHIL), University of Liverpool

Member of JUNIPER Partnership (Joint Universities Pandemic & Epidemiological Research)

Coauthors: Naomi Prosser, Paul Brown, Eamonn Ferguson, Martin Green, Jasmeet Kaler, Matt Keeling, Mike Tildesley

JUNIPER Partnership

JUNIPER is a collaborative network of researchers from across the UK who work at the interface between mathematical modelling, infectious disease control and public health policy.

Who we are

JUNIPER is a partnership that connects epidemic modellers across the country with the aims of building capacity and capability for the UK's epidemiological modelling. A key long-term aim is to ensure that we are better prepared and more resilient to future infectious disease threats, so our research covers a range of infectious diseases that are important regionally, nationally and internationally, as well as supporting underpinning research for strengthening infectious disease modelling.

JUNIPER website

https://maths.org/juniper

Approaches to control infectious disease outbreaks in livestock

Direct action of farmers

The BVDFree England Scheme

What is BVD?

Bovine Viral Diarrhoea or BVD is a highly contagious viral disease of cattle. It is one of the biggest disease issues facing the UK cattle industry. BVD has been estimated to cost between £13 and £31 per cow in Great Britain. The national cost could be as high as £61M per year. (Bennett and Ijpelaar, 2005)

What is the BVDFree Scheme?

BVDFree England is a voluntary industry-led scheme, working to eliminate Bovine Viral Diarrhoea (BVD) from all cattle in England. The key to success is to identify and remove all animals persistently infected (PI) with the BVD virus from the English cattle herd.

Government action

Department for Environment Food & Rural Affairs

Contingency Plan for Exotic Notifiable Diseases of Animals in England

Including Foot and Mouth Disease, Avian Influenza, Newcastle Disease and all other exotic notifiable diseases of animals

Updated on 18 July 2022

Farmer-led Epidemic and Endemic Disease-management (FEED)

FEED project webpage: https://feed.warwick.ac.uk

UKRI Biotechnology and Biological Sciences Research Council

Project motivation

- A knowledge gap on the different factors that drive farmer behaviour in response to an emerging disease.
- Mathematical modelling approaches traditionally treat farmers as passive bystanders & omit variation in disease management behaviours

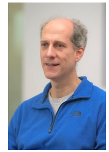
Interdisciplinary team

WARWICK
THE UNIVERSITY OF WARWICK

Infectious disease modelling

Ed Hill

Mike Tildesley



Matt Keeling

GUI development

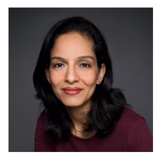
Paul Brown

University of Nottingham
UK | CHINA | MALAYSIA

Veterinary epidemiology

Naomi Prosser

Martin Green



Jasmeet Kaler

Behavioural psychology

Eamonn Ferguson

Study aims

1. Elicit farmers vaccination decisions to an unfolding epidemic and link to their psychosocial and behavioural profiles (within Great Britain)

2. Refine mathematical disease models to capture psychosocial & behaviour change heterogeneities

3. Assess how psychosocial & behaviour change factors impact epidemiological outcomes given a fast-spreading livestock disease

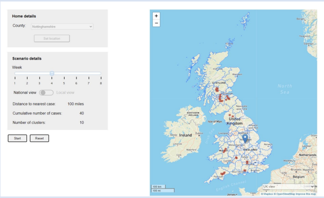
Incorporating heterogeneity in farmer disease control behaviour into a livestock disease transmission model
EM Hill, NS Prosser, PE Brown, E Ferguson, MJ Green, J Kaler, MJ Keeling, MJ Tildesley. (2023)
Preventive Veterinary Medicine.
doi:10.1016/j.prevetmed.2023.106019

Study aims

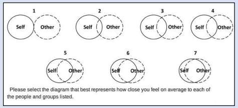
1. **Elicit farmers vaccination decisions to an unfolding epidemic and link to their psychosocial and behavioural profiles (within Great Britain)**

1 Design of a Graphical User Interface (GUI) to act as a core, interactive component of the interview exercise

Visit https://feed.warwick.ac.uk



2 Development and usage of an interview script to elicit farmer disease vaccination behaviours



The script used during the interviews to collect demographic data, explain the hypothetical disease and proceed through the disease outbreak scenario.

County:

Type of cattle: **Beef** **Dairy** **Both**

Thank you for your willingness to take part in this interview.

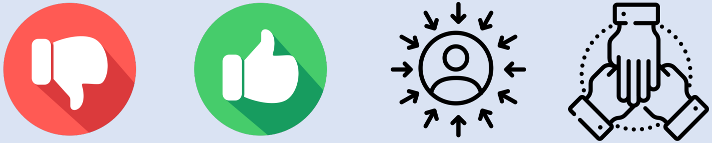
We are interested in capturing the decisions farmers make in an evolving scenario of a disease epidemic. There are no right or wrong answers to the questions, we value your opinion as a farmer responsible for the decisions made about the care of your cattle. We would also like to capture some information about you as a farmer and the type of farm you have.

Imagine you have **won** £700 in a **lottery**. Imagine you had the option to divide some, none or all of this £700, between yourself and the others listed below. You can split the money in any way you see fit, you don't have to give anyone any money or give everyone the same amount. You can decide who gets what, if anything, of the £700. Please indicate how you would like to split the £700 between yourself and these groups (the total divided must equal £700).

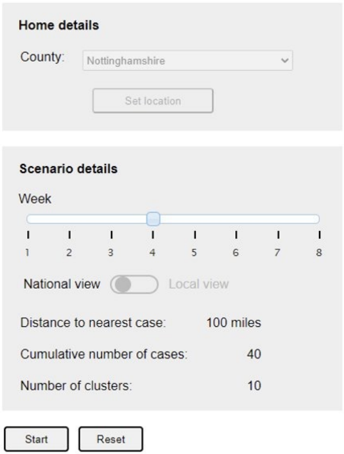
How much of the £700 (some, none or all) would you...

	* Required
Keep for yourself	£
Give to a random unknown farmer	£
Give to a neighbouring farmer	£
Give to a random unknown vet	£
Give to your local vet	£
Give to a stranger	£

3 Grouping of farmer vaccination behaviours in the elicitation exercise



Elicitation methods - GUI



https://feed.warwick.ac.uk/map.html

- Gave a common outbreak experience in terms of distance to the nearest infected herd for all farmers.

Elicitation methods - Questionnaire

Other people and groups

Please indicate how well you agree with each of the following statements.

✱ Required

	Strongly agree	Agree	Neither agree nor disagree	Disagree	Strongly disagree
When dealing with farmers it is better to be careful before you trust them					
I feel respected by the government					
I trust other farmers nationally to be controlling infectious diseases in their herds					
I trust other farmers I meet for the first time					
When dealing with vets it is better to be careful before you trust them					
When dealing with strangers it is better to be careful before you trust them					
In general, one can trust people					
I feel respected by my vet					

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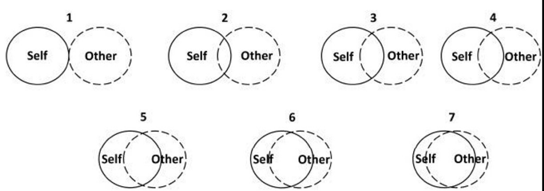


Please select the diagram that best represents how close you feel on average to each of the people and groups listed.

	✱ Required						
	1	2	3	4	5	6	7
Your vet							
The veterinary community in general (i.e. all vets nationwide)							
Your neighbouring farmers							
The farming community in general (i.e. all farmers nationwide)							
The Government							
Your cows							
Dairy farmers in general (i.e. all dairy farmers nationwide)							
Beef farmers in general (i.e. all beef farmers nationwide)							

Elicitation results – GUI simulation

Table: Number of infected herds, distance of the nearest infected herd from the interviewee's herd and number of farmers that vaccinated each week during the disease epidemic scenario.

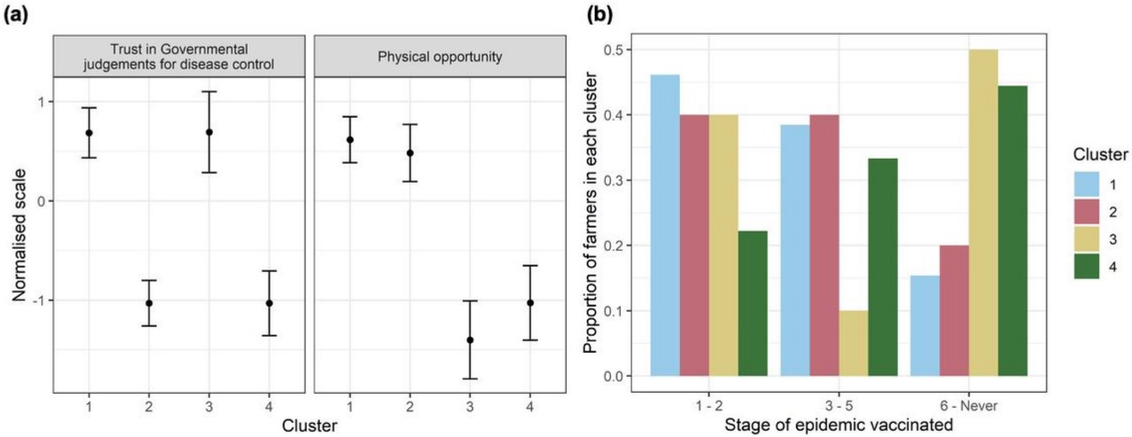
Stage of epidemic	Time since previous stage (weeks)	Number of infected herds (in GB)	Distance to nearest infected herd (km)	Number of farmers vaccinating (/60)
1	2	0	>500*	8
2	2	2	322	16
3	1	10	322	5
4	1	40	161	14
5	1	100	161	1
6	1	150	48	10
7	1	450	16	3
8	1	600	5	1
*Epidemic confined to southern-central France				

- Sixty farmers (39 beef & 21 dairy) participated, with variability apparent in when they would use preventative vaccination.

Elicitation results – Farmer groupings

- Using k-means clustering, four groups gave best fit when clustering by two most stable covariates (trust in Governmental judgements for disease control, high physical opportunity)

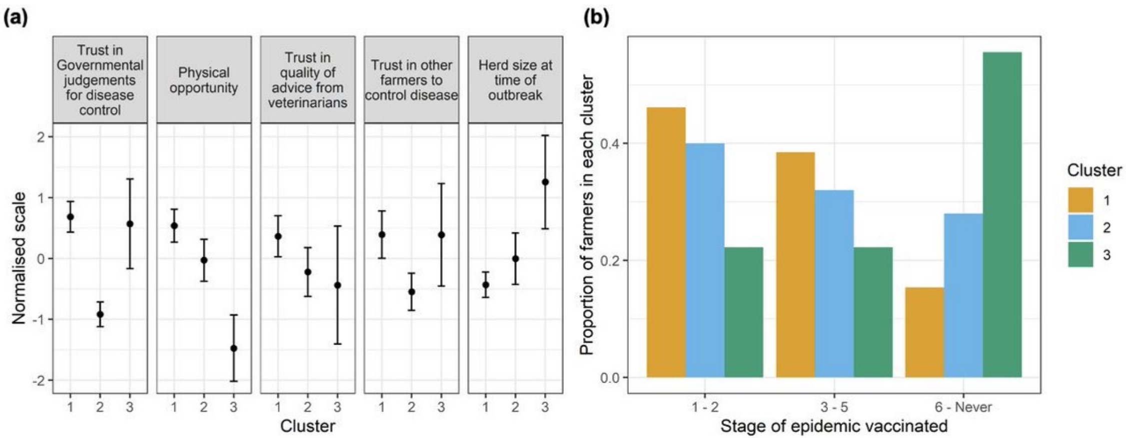
Figure: Farmer groups from k-means clustering conducted on two most stable covariates. **(a)** Mean and 95% confidence interval scores of the covariates for each group. **(b)** Proportion of farmers in each group that vaccinated in different stages of the outbreak.



Elicitation results – Farmer groupings

- Grouping using five most stable covariates, three groups gave best fit.
- Additional covariates: Trust in vet advice, trust in other famers to control disease, herd size.

Figure: Farmer groups from k-means clustering conducted on five most stable covariates. (a) Mean and 95% confidence interval scores of the covariates for each group. **(b)** Proportion of farmers in each group that vaccinated in different stages of the outbreak.



Study aims

1. Elicit farmers vaccination decisions to an unfolding epidemic and link to their psychosocial and behavioural profiles (within Great Britain)

2. **Refine mathematical disease models to capture psychosocial & behaviour change heterogeneities**

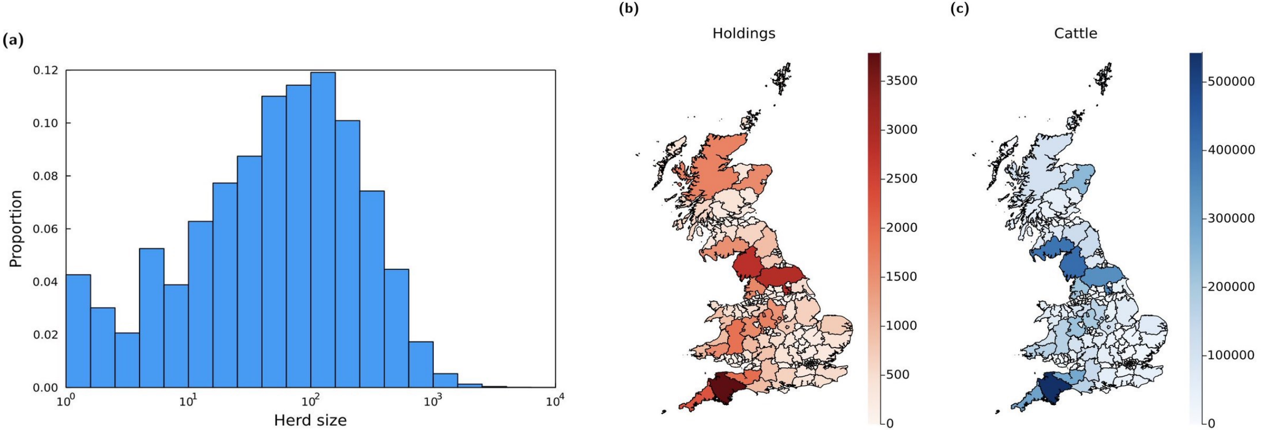
Data-driven spatial model framework with epidemiological and behavioural layers.

3. Assess how psychosocial & behaviour change factors impact epidemiological outcomes given a fast-spreading livestock disease

Modelling methods - Cattle data

- Data from the **Great Britain Cattle Tracing System** (we used records from 2020; contained approx. 60,000 holdings)
- **Cattle demography:** Per holding, average cattle herd size
- **Cattle holding locations:** Per holding, easting-northing co-ordinates.

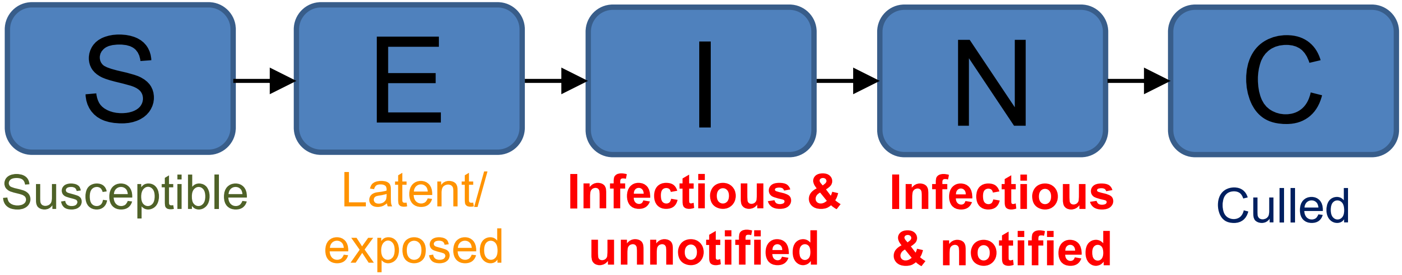
Figure: (a) Distribution of cattle herd sizes. **(b)** Number of holdings with cattle per region. **(c)** Number of cattle per region.



Modelling methods – Disease states

- **Epidemiological unit:** Cattle holding (farm).

- **Spatial model**, based loosely on the dynamics of FMD.
  - **Force of infection dependencies:** Number of livestock, livestock type specific transmissibility and susceptibility, distance between premises.
  - **Infection to infectiousness (latent period):** 5 days
  - **Infection to notification:** 9 days
  - **Infection to culled:** 13 days



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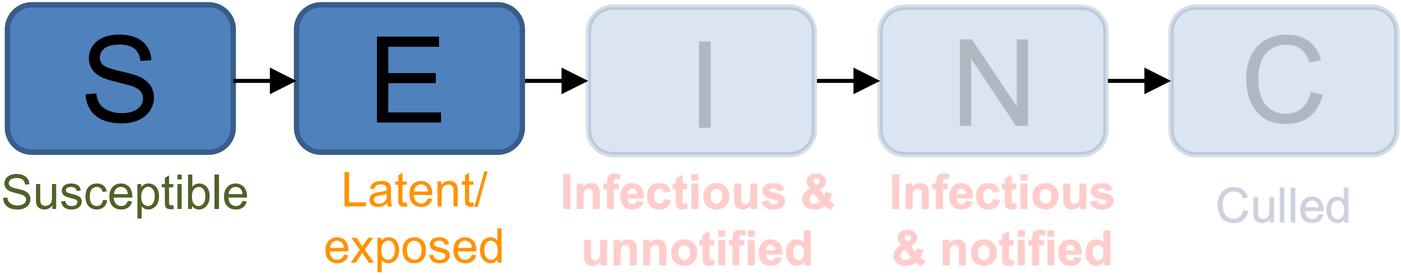

Modelling methods – Force of infection

Force of infection on premises i from premises j: $\lambda_{ij} = t_c N^q_{c,j} N^p_{c,i} K(d_{ij})$

- Infected premises contribution: Dependent on herd size
- Susceptible premises contribution: Dependent on herd size
- Transmission kernel: Force of infection between premises dependent on the distance between them.

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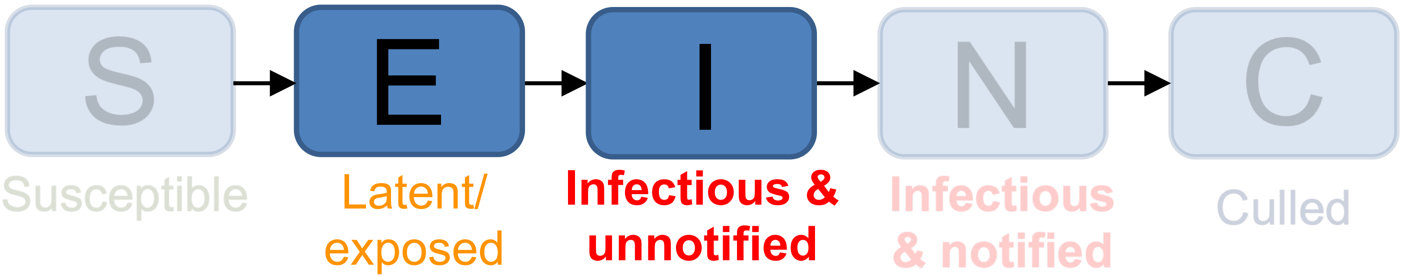

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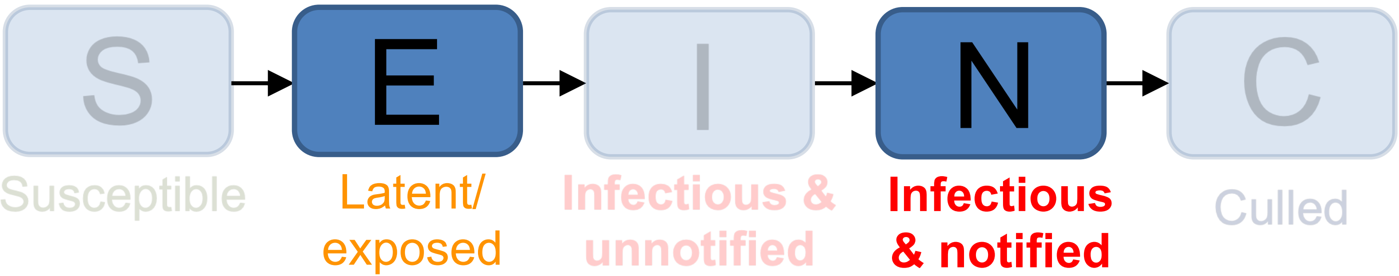

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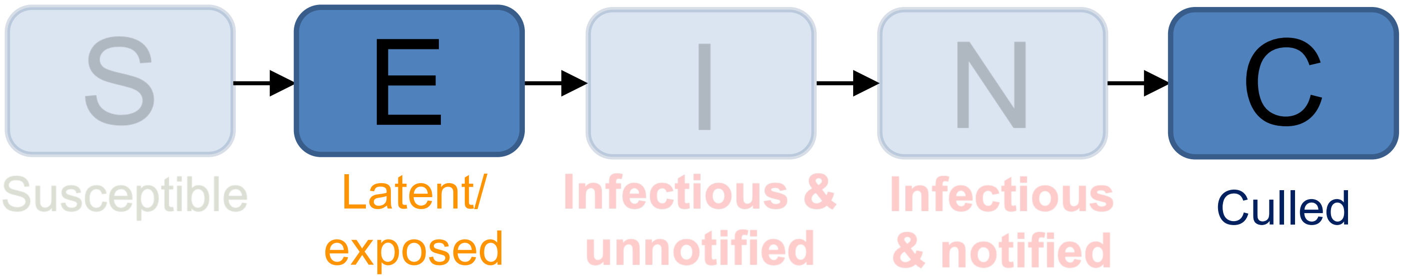

Modelling methods – Behavioural configurations

Uncooperative Only control is cattle being removed at holdings with confirmed infection. i.e. No holdings apply vaccination.

Homogeneous: Non-data informed
Farmer vaccinates when infection is within:

- Strong parasitism: 50km
- Weak parasitism: 320km
- Mutual cooperation: Before pathogen emergence

Heterogeneous: Non-data informed
Even split across different groups.

- Coop-Parasitism-Free riders (FR)
- Coop-Parasitism

Heterogeneous: Data informed
Parameterised using interview results

- Trust expectancy (two covariate model)
- Herd size dependent (five covariate model)

Study aims

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2. Refine mathematical disease models to capture psychosocial & behaviour change heterogeneities

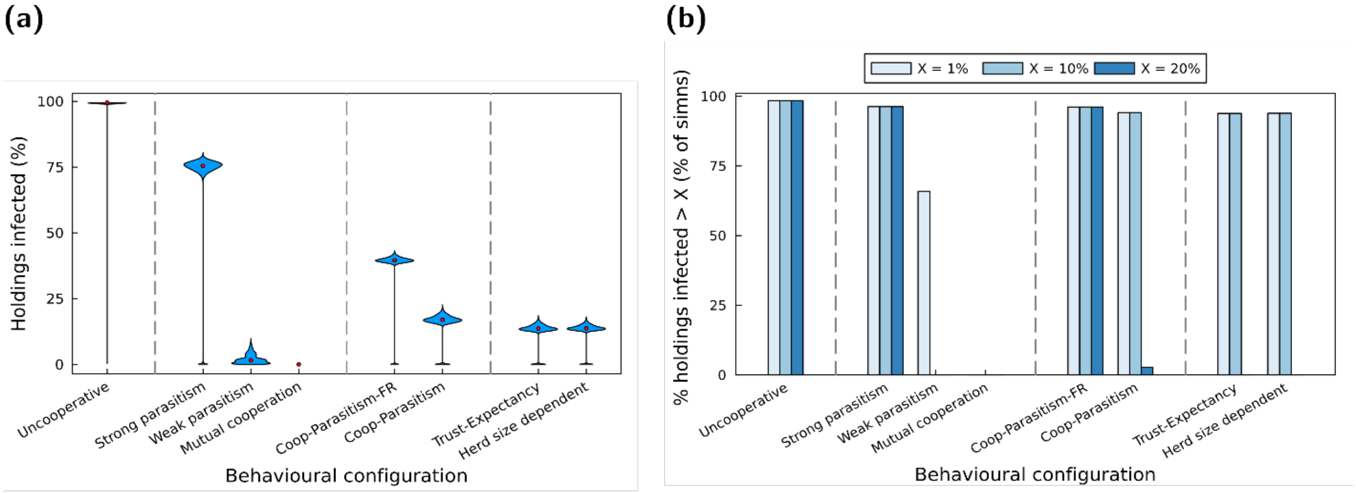
3. **Assess how psychosocial & behaviour change factors impact epidemiological outcomes given a fast-spreading livestock disease**

Spatial stochastic simulations of a fast-spreading epidemic process in Great Britain amongst cattle holdings:

- Per behavioural configuration, ran 500 replicates for each of the 89 seed region locations.
- Per simulation replicate, seeded infection in a randomly selected cluster of three premises.

Modelling results – Epidemiological metrics

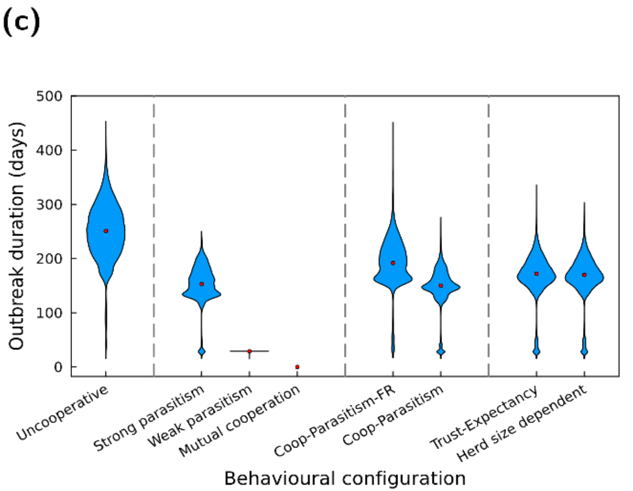
Figure: For each behavioural configuration: **(a)** Distribution of percentage of holdings infected; **(b)** Percentage of simulations exceeding the stated final size.

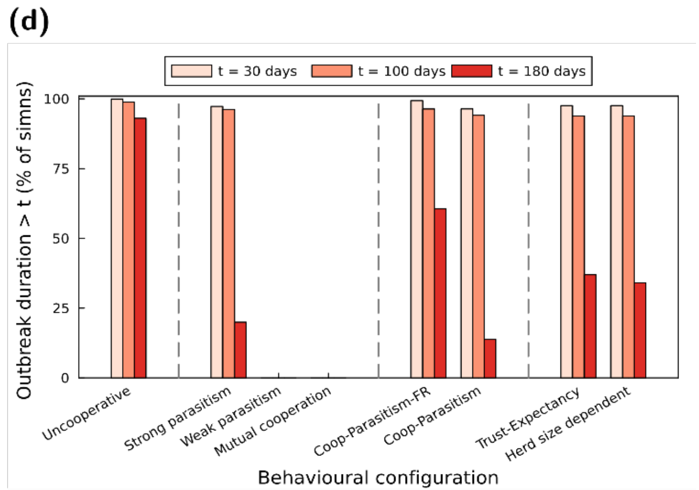


➢ Comparing homogeneity in farmer behaviour vs data-informed heterogeneity in farmer behaviour: **Disconnect in outcomes**

Modelling results – Epidemiological metrics

Figure: For each behavioural configuration: **(c)** Distribution of outbreak duration; **(d)** Percentage of simulations exceeding the stated outbreak duration.



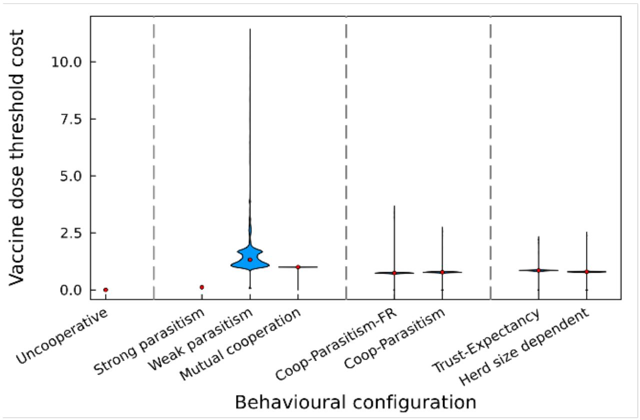


➢ Comparing homogeneity in farmer behaviour vs data-informed heterogeneity in farmer behaviour: **Disconnect in outcomes**

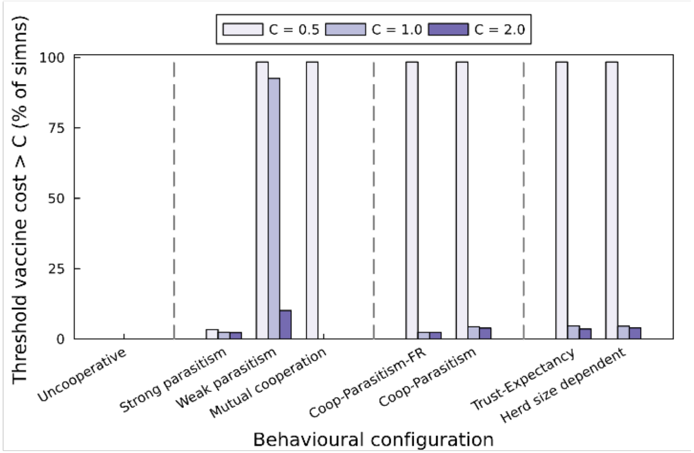
Modelling results – Health economic metrics

Figure: For each behavioural configuration: **(e)** Distribution of vaccine dose threshold costs; **(f)** Percentage of simulations exceeding the stated vaccine dose threshold cost.

(e)



(f)

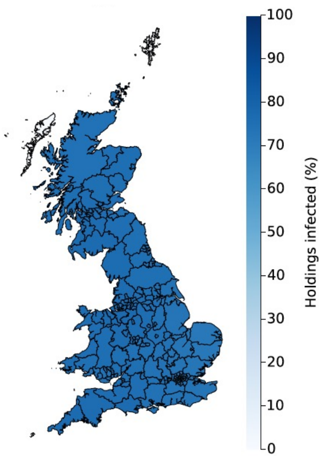


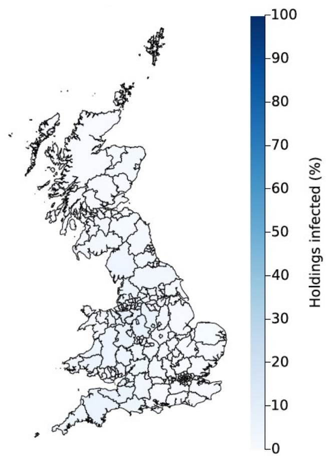
- **Vaccine dose threshold cost:** Maximum cost of a single single vaccine dose so the total monetary cost for that behavioural scenario (across vaccines and losses due to infection) does not exceed the monetary cost of infection incurred in the baseline scenario (uncooperative behavioural configuration).

Modelling results – Role of seed infection region

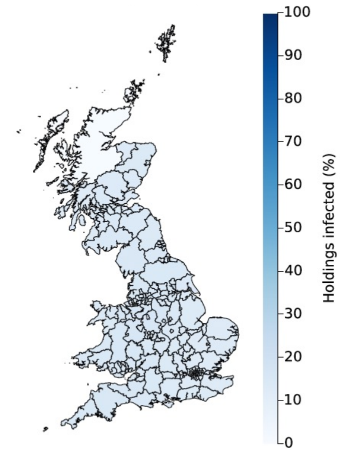
Figure: Median percentage of holdings infected, dependent on region of outbreak emergence and behavioural configuration. Statistics computed from 500 replicates per scenario.

Homogeneous behaviour (non-data informed)





Heterogeneous behaviour (data informed)



Vaccinate when infection within:

50km **320km**

Limitations & further work

Elicitation

- Behavioural cluster analysis not feasible at regional level
- Are other intervention practices available to farmers

Modelling

- Focused on a limited set of interventions
- Considered a single set of epidemiological parameters

Open questions– what are the next steps?

- Support to establish longitudinal elicitation studies
- Tailored elicitation exercises to instruct behavioural group attributes amongst farmers towards control of enzootic diseases

Implications

- **A demonstration of a conjoined epidemiological and socio-behavioural workflow in action!**

- **Encourage consideration of actions of individual farmers in policy frameworks for tackling future livestock disease outbreaks**

Other activities related to epidemiological-behavioural modelling

1. Mathematical Interdisciplinary Research at Warwick (MIR@W)/JUNIPER workshop on "*Mathematical modelling of behaviour to inform policy for societal challenges*"
2. Mathematics in Medical and Life Sciences: Special issue on Behavioural Epidemiology
3. UKRI interdisciplinary epidemic preparedness call: Networking group on *"Tackling epidemic threats by advancing the science of human interactions and infection"*
4. INI satellite program: Maths of human behaviour

1. MIR@W/JUNIPER workshop

What? **Mathematical modelling of behaviour to inform policy for societal challenges**

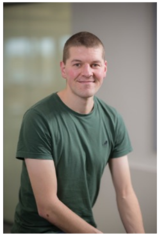
When & Where?

- Monday 10 June 2024
- Warwick Mathematics Institute, University of Warwick, Coventry

Organising committee

Kirsty Bolton (Nottingham)

Stephen Parnell (Warwick)



Emily Nixon (Liverpool)

Martine Barons (Warwick)

Ed Hill (Warwick)

1. MIR@W/JUNIPER workshop

Invited speakers

- David Haw (Lecturer in Mathematics for Health, University of Liverpool) - Linking epidemiological and behavioural models in public health.
- Anne Kandler (Senior Scientist, Department of Human Behavior, Ecology and Culture, Max Planck Institute for Evolutionary Anthropology) - Applied mathematician interested in the underlying principles of cultural change especially in changing environmental conditions.
- Ruth McCabe (Postdoctoral Researcher, Imperial College London) - Communication of modelling results to non-technical audiences.
- Alice Milne (Senior Research Scientist - Agricultural Systems Modeller, Rothamsted Research) - Linking epidemiological and behavioural models in plant health.
- Suzy Moat & Tobias Preis (Professors of Behavioural Science & Co-directors of the Data Science Lab, Warwick Business School, University of Warwick) - Measuring real world actions and events with online data.
- Kavita Vedhara (Professor of Health Psychology, Cardiff University) - Health psychologist with expertise in the inter-relationships between psychological factors and health and disease outcomes.

Contributed talks presenters

- Elaine Ferguson (Research Associate, School of Biodiversity, One Health and Veterinary Medicine, University of Glasgow) - Infectious disease ecologist working on modelling approaches to study the infectious disease dynamics of rabies.
- Mark Lynch (PhD student, Mathematics for Real-World Systems Centre for Doctoral Training, University of Warwick) - Research interests in applications of machine learning and neural networks to epidemiological models.
- Luisa Fernanda Estrada Plata (MSc student, Mathematics for Real-World Systems Centre for Doctoral Training, University of Warwick) - Applied mathematician with research interests in behavioural science.
- Matt Ryan (CERC Postdoctoral Fellow, Commonwealth Scientific and Industrial Research Organisation - CSIRO) - Applied mathematician exploring the interface of infectious disease modelling and behavioural science to define better "business-as-usual" forecasting models.
- Fanqi Zeng (Postdoctoral Researcher, Department of Sociology, University of Oxford) - Sociologist working on projects related to the study of global fake medicines trading and organised crime.

Slides and talk recordings that can be shared are available on the event webpage

https://warwick.ac.uk/fac/sci/maths/research/miraw/days/modellingbehaviour

2. Mathematics in Medical and Life Sciences: Special issue on Behavioural Epidemiology

Submit a Manuscript to the Journal

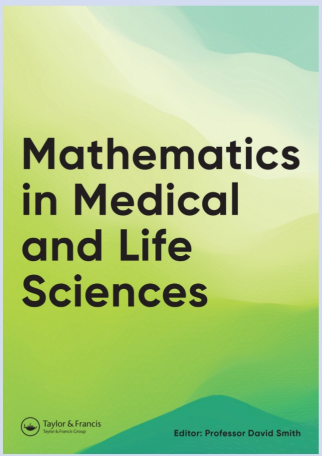
Mathematics in Medical and Life Sciences

For a Special Issue on

Behavioural Epidemiology

Manuscript deadline
31 March 2025

OPEN ACCESS



Special Issue Editor(s)

Edward Hill, *University of Warwick*
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Stephen Beckett, *University of Maryland*
beckett@umd.edu

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3. UKRI interdisciplinary epidemic preparedness call: Networking group on “Tackling epidemic threats by advancing the science of human interactions and infection”

Seeking better understanding of human interactions

The project is being led by Dr Jonathan Read at Lancaster University and Professor Kavita Vedhara at Cardiff University.

They will bring together epidemiologists, behavioural and computer scientists, philosophers and other academics from UK universities and government agency stakeholders.

Our approach, in this first phase of funding, is to **establish a research network of academics, governmental agencies, commercial partners and the public, with which we will undertake workshops, meetings and scoping reviews to design a programme of future research** to advance the science of human interactions relevant to infectious disease transmission.

https://www.ukri.org/news/diverse-partnerships-will-help-fight-future-disease-outbreaks/

4. INI satellite program: Maths of human behaviour

Why?

- Inability to forecast behaviour limits predictive power of epidemic models.
- Behaviour important driver of dynamics in other fields (e.g. energy systems).
- Need for a new interdisciplinary field akin to mathematical biology?

Details?

- 4-week programme, July/August 2026
- Venue: School of Mathematical Sciences, University of Nottingham

Who?

Kirsty Bolton (Nottingham)

Ed Hill (Liverpool)

Ellen Zapata-Webborn (UCL)

Deepak Padmanabhan (Queens')

Matt Ryan (CSIRO)

Jon Ward (Leeds)

4. INI satellite program: Maths of human behaviour

What?

- Participants spanning behavioural sciences, complex systems, statistics, data science, and epidemic and energy systems modelling.

- **Week 1**: ‘Start-up School’ featuring a cross-section of behavioural scientists
- **Weeks 2&3**: Group work on three ***challenges*** across the proposed key behaviours of **mobility, sociality and protectionism:**
  - Abstraction of real-world systems
  - Societal response to policy
  - Causal relationship between information and behavioural response
- **Week 4**: Outward facing workshop presenting progress on each challenge, networking with stakeholders, and exploring the international context.

Study implications

- Demonstrated a conjoined epidemiological and socio-behavioural workflow in action!
- Encourage consideration of actions of individual farmers in policy frameworks for tackling future livestock disease outbreaks

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