Institution: University of Cambridge

Unit of Assessment: UoA5

Title of case study: Epidemiological models to underpin the management of emerging plant diseases

1. Summary of the impact (indicative maximum 100 words)

Since 2004, researchers in Cambridge have developed a series of generic and flexible models to predict the spread of plant diseases in agricultural, horticultural and natural environments. These now underpin policy decisions relating to the management and control of a number of such diseases, including sudden oak death and ash dieback in the UK (by Defra and the Forestry Commission), and sudden oak death in the US (by the United States Department of Agriculture). This has subsequently had an impact on how practitioners manage these diseases in the field, and on the environment through the implementation of disease mitigation strategies. In the case of ash dieback, the Cambridge work has also directly contributed to public involvement in mapping the spread of the disease.

2. Underpinning research (indicative maximum 500 words)

The Epidemiology and Modelling Group in the Department of Plant Sciences has worked on emerging plant diseases for many years. Led by Professor Chris Gilligan (Professor 1999-present), the group specialises in analysing the factors that influence and control invasion, persistence and variability of plant diseases using a combination of experimentation and modelling. Over the past ten years, this has led to the development of a number of new models and methodologies for the study and management of disease spread, for both persistent pathogens and emerging epidemics.

In 2004, the group published[1] a stochastic model that could be used to predict the risk of disease spread and to identify the potential (in terms of probability of success versus risk of failure) for control and management of Rhizomania in sugar beet, a major economic threat to the sugar industry in the UK. For the first time, the work concluded that if control strategies were to be successful, these must reflect the intrinsic temporal and spatial scales of epidemics; to address this, the group published a refined model in 2007[2]. Also in 2007, the group demonstrated how epidemiological models could be linked with economic models to determine optimal treatment regimes for discrete epidemics in terms of efficacy and cost[3]. This is of particular importance when resources are limited (until this point, most models of treatment scenarios had focused on either epidemiological or economic considerations).

In 2008, the group proposed a novel statistical approach for optimising the usefulness of data drawn from past epidemics and their control strategies, in order to help manage future outbreaks[4]. This illustrated at what point partial information (essentially all that is available in the early stages) should be used to estimate dispersal and transmission parameters for emerging epidemics with any degree of accuracy, thus improving the precision of efficacy predictions for different control strategies. Based on previous work (above), the model included both spatial and temporal considerations.

More recently, the group combined the spatio-temporal work with geographic modelling to predict disease spread in realistic landscapes and under realistic weather conditions, for citrus canker[4] and sudden oak death in the United States[5,6] (this work was led by Gilligan and undertaken in collaboration with colleagues in the US and Singapore, who contributed data and on-the-ground expertise). Landscape heterogeneity of host availability and environmental conditions have a significant influence on the scale and severity of real-time epidemics; the addition of these components to stochastic epidemiological models significantly increased the predictive power of the models for understanding both disease dynamics and the likely impact of control strategies. The work on sudden oak death also set out a process for the development of hazard maps, allowing regulators or policy makers to identify regional, country or even continental areas at particular risk from a particular pathogen, were it to be accidentally introduced there.

3. References to the research (indicative maximum of six references)

Names of Cambridge-based scientists are underlined

1. Stacey, A. J., Truscott, J.E., Asher, M.J.C. and Gilligan, C.A. (2004) A model for invasion and spread of rhizomania in the UK: implications for disease control strategies. *Phytopathology*

94: 209-215. doi:10.1094/phyto.2004.94.2.209
2. Gilligan C.A, Truscott J.E. and Stacey AJ (2007) Impact of scale on the effectiveness of disease control strategies for epidemics with cryptic infection in a dynamical landscape: an example for a crop disease. *J. Roy. Soc. Interface* **16:** 925-934. doi:10.1098/rsif.2007.1019
3. Forster, G.A. and Gilligan, C.A. (2007) Optimising the control of disease infestations at the landscape scale. *Proc. Nat. Acad. Sci.* **104:**.4984-4989. doi:10.1073/pnas.0607900104
4. Cook A.R, Gibson G.J, Gottwald T.R, Gilligan C.A. (2008) Constructing the effect of alternative intervention strategies on historic epidemics. *J. Roy. Soc. Interface* **5:** 1203-1213. doi:10.1098/rsif.2008.0030
5. Meentemeyer, R.K., Cunniffe, N.J., Cook, A.R., Filipe, J.A.N., Hunter, R. D., Rizzo, D. M. & Gilligan, C.A. (2011) Application of stochastic epidemiological models to realistic landscapes: spread of the sudden oak death pathogen in California 1990–2030). *Ecosphere* **2**: art17. doi:10.1890/ES10-00192.1
6. Filipe, J., Cobb, R., Meentemeyer, R.K., Cook, A.R., Rizzo, D.M. & Gilligan, C.A. (2012) Landscape epidemiology and control of pathogens with cryptic and long-distance dispersal: sudden oak death in northern Californian forests. *PLoS Comp. Biol.* e1002328. doi:10.1371/journal.pcbi.1002328

Research Grants: CAG was lead or sole PI in all

- Defra: *Epidemiological modelling to inform management strategies for sudden oak death in England and Wales £684k* (*2010-13*)
- USDA-APHIS *Disease modeling via stochastic simulation to test disease control/mitigation strategies and maximize regulatory intervention* (jointly with Dr Tim Gottwald, USDA-ARS, Fort Pierce, FL) $650k (2007-12)
- BBSRC-INRA: *Epidemiological and evolutionary models for invasion of disease.* £817k (2006-12)
- Defra: *Development and testing of an epidemiological framework to optimise the detection and intervention strategies for plant pathogens of statutory concern* (jointly with Dr F. van den Bosch, Rothamsted Research) £715k 2006-09
- BBSRC: Professorial Research Fellowship – *Disease in a changing landscape* £500k (2004-10)
- USDA-FS: *Optimization of management strategies for sudden oak death using epidemiological models and GIS technologies* (with Dr D. Rizzo, UC Davis, Dr R Meentemeyer, Univ. N. Carolina) $185k (2006-11)

4. Details of the impact (indicative maximum 750 words)

The main areas of impact of the research as set out in section two are as follows:

- Impacts on public policy: policy decisions have been informed, control measures for infections have improved
- On practitioners and services: these have used research findings in conducting their work.
- On the environment: planning decisions have been informed; the management of environmental risks and hazards have been changed.

In order to facilitate practical use of their research, the group developed fast computational methods to enable large numbers of simulated epidemics to be run in order to compare and screen different 'what-if' control scenarios, from which to select effective strategies and reject those with high risk. The methods and code were assembled into a more broadly applicable epidemiological tool-box for invading pathogens in crop, forest and natural environments at regional and country-wide scales, and which is now freely available to policy makers and relevant others[7].

Sudden oak death

Despite its name, sudden oak death has a wide host range, infecting more than 100 economically and ecologically important woody hosts. It is currently invading woodlands and heathlands in the UK, and putting at risk woodlands in California.

Impacts on public policy

In Aug 2008, Gilligan's group was approached by the Forestry Commission and Defra to introduce an objective means of comparing different scenarios of disease spread (see Defra grants, section

3). From 2009, UK national strategies and practical sampling and control regimes for sudden oak death have been explicitly based on the resultant models[8,9]. Throughout England and Wales, they are used to inform, adjust and implement sampling and control policies (Involving 55,000 km of targeted aerial survey as part of a £25M 'eradication and control' management scheme) that hitherto had been ad hoc.

The models have also been used (since 2009) in collaboration with the US Department of Agriculture (USDA) to investigate and screen strategies for management of sudden oak death in California, which is causing major losses in vegetation in the State. The models have demonstrated the value of early detection and control, and been used to determine which regions of the state are likely to be at most risk. They have also been used to demonstrate that creating barriers by removing large areas of vegetation is unlikely to work. More widely, the models have been used inform US policy advisers and policy makers about the risks of spread of sudden oak death in Eastern states of the US and of citrus diseases in Florida and California[10].

Impacts on practitioners and services, impacts on the environment
As control involves felling trees and removal of shrubs around infected sites, the models are used by practitioners to gauge the probable epidemiological and economic effectiveness of different culling distances and frequency of revisit. They also guide aerial and ground surveys for the disease, by generating 'hazard maps' identifying where disease would have most impact.

<u>Chalara fraxinia – ash dieback</u>
Following the discovery of *Chalara fraxinia*, a fungal pathogen that causes dieback of ashtrees, in the UK for the first time in 2012, and based on the group's prior expertise, the Government in consultation with the Government Chief Scientific Adviser (GCSA) commissioned them (through Defra) to model the potential spread in the UK[11]. The rapid Government response was based on the commercial and leisure values of ash in the UK; it is one of the most valuable native hardwoods (comprising ~15% of the standing UK hardwood stock) and one of the most common trees in urban settings.

Impacts on public policy
The group adapted and enhanced the epidemiological toolbox to develop a model to predict the likely modes of introduction of Chalara and future spread within the UK. The results were submitted to Defra and to the GCSA's Expert Committee[12] with a final research report which was submitted to Defra with a final report in March 2012[13]. Defra's subsequent Chalara Management Plan was published March 2013[14], and is extensively based on the Cambridge model (which is cited throughout). For example:

- 'Modelling the impact of Chalara' (p.13) '*This priority map* [map 3, combining two maps from the Cambridge model] *is already being used to focus the efforts of Defra and Forestry Commission inspectors who are tracing deliveries of young ash trees over recent years and checking for signs of infection*. *Details of how the modelling has been used to inform other management decisions are set out throughout the plan.'*

The group's work is therefore the foundation for Government decision making in terms of how to manage and where to manage the disease.

The UK Devolved Administrations have developed their own responses to Chalara, also based on the Cambridge model. The Chalara Management Plan for Wales[15] (March 2013) states that '*the University of Cambridge modelling work tells us that the effect of slowing the spread of the disease will be relatively short-lived. This means that we should not rush to take actions … these actions would be costly, potentially have adverse consequences for the environment, and are unlikely to have widespread support of landowners and woodland managers, in the light of the limited effects on disease predicted by the Cambridge model*.' In Ireland, the Department of Agriculture and Rural Development (NI) and the Department of Agriculture, Food and the Marine (Ireland) jointly produced an All Ireland control strategy for Chalara[16] (July 2013), which used the Cambridge model to predict the likelihood of possible airborne incursion of Chalara spores into Ireland, and to prioritise the management strategy for the disease on the island. The model is also being used to inform control strategies in Scotland.

In May 2013 Defra published a policy paper entitled ‘Chalara in Ash Trees: A Framework for Assessing Ecosystem Impacts and Appraising Options’[17]. This highlights that the Chalara work, including a fundamental role for modeling, provides a framework for the assessment of other potential such diseases in the future, given the limited experience to date of taking a scientific approach to managing the impacts of plant and tree diseases.

Impacts on practitioners and services
Across the UK and Ireland, the Forestry Commission, practitioners in landscape and estate management, and those in other horticultural professions are following Government guidance (based on the various management plans, and therefore on the Cambridge model) in dealing with suspected and confirmed cases of Chalara[18].

Impacts on the environment
The Management Plan deals with both the management of ash trees as a natural resource, and the management of Chalara as an environmental risk.

Impacts on society, culture and creativity – public debate has been stimulated or informed by research: Professor Gilligan has been interviewed about Chalara on BBC Newsnight, Countryfile, News 24, BBC Radio 4 Today Programme, Material World, Farming Today, World at One, plus local radio and several press interviews. The ‘Tree Alert’ and ‘ashtag’ apps are enabling the general public to get involved with mapping the spread of the disease across the UK and Ireland[19,20].

5. Sources to corroborate the impact (indicative maximum of 10 references)

7. www.webidemics.com
8. Scientist in charge of Coordination of Sudden oak death management, Forestry Commission (FC) has provided evidence of the use of the models to inform FC Policy on practical control decisions about where and how to control sudden oak death on FC land.
9. Co-ordinator for Defra Sudden oak death/Ramorum programme, Defra has provided evidence of the use of the models to inform practical decisions about where to sample and how to control the spread of sudden oak disease on Rhododendron
10. Research Leader, USDA Florida: has provided evidence of impact of models in practical disease control for tree diseases in the US.
11. Deputy Director, Evidence Defra has provided evidence of the impact of the models within Defra
12. The Government Chief Scientist (2008-13), has provided evidence of the impact of the models for Chalara.
13. Research Report to DEFRA: Chalara Modelling Report: Incursion, Risk and Sampling
14. Defra Chalara Management Plan (March 2013): www.gov.uk/government/publications/chalara-management-plan
15. Chalara Management Plan for Wales, March 2013: http://www.forestry.gov.uk/pdf/ChalaraManagementPlanWales.pdf/$file/ChalaraManagementPlanWales.pdf
16. All Ireland Chalara Control Strategy, July 2013: www.agriculture.gov.ie/media/migration/forestry/ashdiebackchalara/AllIrelandChalaraControlStrategyJuly13.pdf
17. Chalara in Ash Trees: A Framework for assessing ecosystem impacts and appraising options (Defra Policy Paper), May 2013
18. Forestry Commission and Royal Forestry Society Chalara Control Plan Update, March 2013. http://www.rfs.org.uk/files/Chalara%20Control%20Plan%20Update3_%202013.pdf
19. Tree alert app: https://itunes.apple.com/gb/app/tree-alert/id582936354?mt=8
20. Ashtag app: www.ashtag.org