Institution: University of Cambridge		
Unit of Assessment: UoA5		
Title of case study: Protecting global food production and woodland environments: forecasting and managing plant disease through epidemiological modelling		
Period when the underpinning research was undertaken: 2008-2017		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Christopher A. Gilligan	Professor of Mathematical Biology	1977 – present
Period when the claimed impact occurred: 2015-2020		
Is this case study continued from a case study submitted in 2014? N		

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

Models developed and tested by the Epidemiology and Modelling Group at the University of Cambridge, led by Prof. Chris Gilligan, have been used to inform government policy and practical implementation of surveillance and control methods for major epidemic diseases of crop plants and natural vegetation. The impacts of this include:
1. Forecasting wheat rust disease to enable up to 500,000 smallholder farmers in Ethiopia to take timely preventative action.
2. Predicting the spread of and control options for cassava brown streak disease in ten countries in Sub-Saharan Africa, leading to governmental policy changes.
3. Informing strategy for the control of banana bunchy top virus for the Australian banana industry, worth AUD605M to the country's economy.
4. Informing surveillance and management of tree diseases ash dieback, larch ramorum, and oak processionary moth in the UK, and citrus greening in California, US.

2. Underpinning research (indicative maximum 500 words)

Research at the University of Cambridge was motivated by the need for an epidemiological toolkit to mitigate the impact of emerging epidemics that threaten crop plants and food security, as well as natural vegetation such as forest and woodland trees. The toolkit is sufficiently tested and suitably flexible to enable rapid and effective deployment to predict the rate of disease spread and cost-effective intervention options as epidemics occur in real time.

The idea for the research was developed during a BBSRC Professorial Research Fellowship on *Disease in changing agricultural environments* awarded to Prof. Chris Gilligan at the University of Cambridge (2004-10). This led to the development of a theoretical framework for plant disease epidemics spreading through heterogeneous landscapes. In 2008, Prof. Gilligan's group assembled a series of flexible epidemiological models together with computational and statistical methods for parameter estimation, as well as economic and meteorological models, into an 'epidemiological toolkit' to deal with emerging epidemics of pathogens affecting crops, semi-natural and natural vegetation [R1, R2, R3], which can have devastating consequences [R3]. The methods have been extensively tested in the same period using a range of pathogens (including fungi, oomycetes, bacteria, viruses) and insect vectors, and extended to include insect pests. Fundamentally, these models track the infection/infestation status of individual sites using stochastic, spatially explicit epidemic models. A site may be an individual plant, a field, farm, village or other grouping and the models scale from what happens within individual fields and farms, through villages and districts up to whole countries and beyond to continental disease spread [R1,R2]. The basic formulation of the models is recognisable as a susceptible-infected-removed (SIR) compartmental model, familiar in medical epidemiology. The innovations come in the extensions of compartments to allow for multiple sources of infection (trade, vector) as well as distinguishing a range of infection classes [R1, R2, R3, R4]. These include cryptic classes that are infectious but not symptomatic and detectable classes that can only be identified by diagnostic methods (visual, molecular, machine-learning imaging of symptoms). In this way it is possible, to predict the present status of disease, which is routinely unknown, as well as the future spread. The models are stochastic to allow for inherent variability of epidemic spread and other uncertainties, for example, knowledge of dispersal characteristics. Outputs therefore comprise probability distributions that allow estimation of spreading risk and identification and comparison of scenarios for epidemic control that have low risks of failure given the present states of knowledge [R1, R2, R3, R4].

The models incorporate:

- *crop layers* (to describe the density, connectivity and timing of target crops and, where appropriate, alternative hosts);
- *environment layers* (to describe changing weather variables; typically, these involve access to historic and forecast meteorological data);
- *pest/vector layers* (to describe the dispersal and transmission characteristics and yield impacts of target pests);
- *grower-activity layers* (to reflect agronomic and grower behaviour, including deployment of control). [R5]

Long-distance spore dispersal typical of pathogens such as wheat rusts, which can survive and travel for multiple days in turbulent airflow and infect hosts hundreds to thousands of kilometres away, are modelled using meteorologically-driven, Lagrangian dispersal models. These are adapted from UK Met Office models, notably Numerical Atmospheric-dispersion Modelling Environment (NAME), which was originally used to model dispersal of radionuclides, ash clouds and non-biological propagules. Adaptations for living spores and insects require allowance for death from UV radiation during turbulent wind dispersal. In work published in 2017, the dispersal models were coupled with meteorologically-driven models incorporating criteria for infection. [R5]

Parameter estimation is an essential component of the toolkit with Bayesian methods including Markov chain Monte Carlo and Approximate Bayesian Computation, developed and optimised for use in extracting signals for dispersal characteristics from often heterogeneous and incomplete landscape-scale surveillance data. All the models have been optimised to allow rapid computation of multiple stochastic simulations, as for example with the spread of a cassava disease vectored by insect and trade, resolved at 1 km resolution across 20 sub-Saharan countries. [R4]

This body of research on epidemiological modelling has been implemented in four different contexts to generate positive impacts on the management of damaging plant diseases.

Prof. Gilligan's Epidemiology and Modelling group members contributing to this work were: Dr R.O.J.H, Stutt, Dr Anna Szyniszewska, Dr Marcel Meyer, Dr David Godding, Dr Cerian Webb, Dr Matt Castle, Dr Yevhen Suprunenko, Dr Hola Adraky, Dr Clare Allen-Sader, Dr Jacob Smith Dr Tamas Mona, and Dr Renata Retkute in addition to Prof. Gilligan.

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

R1. Gilligan, C.A. (2008) Sustainable agriculture and plant disease: an epidemiological perspective. *Philosophical Transactions of the Royal Society, Series B.* **363:** 741-759.
R2. Gilligan, C.A. & van den Bosch, F. (2008) Epidemiological models for invasion and persistence of pathogens. *Annual Review of Phytopathology.* **46:** 385-418.
R3. Boyd, I.L., Freer-Smith, P.H., Gilligan, C.A., Godfray, H. C. J. (2014) The consequence of tree pests and diseases for ecosystem services. *Science* **342:** 1235773-1-8. doi 10.1126/science.1235773

R4. Parry, M.F., Gibson, G.J., Parnell, S., Gottwald, T. R., Irey, M. S., Gast, T. C. & Gilligan, C. A. (2014) Bayesian inference for an emerging arboreal epidemic in the presence of control *Proceedings of the National Academy of Science USA* 117: 6258–6262, doi: 10.1073/pnas.1310997111.
R5. Meyer, M. Cox, J.A., Hitchings, M.D.T., Burgin, L., Hort, M.C., Hodson, D.P., Gilligan, C.A. (2017) Quantifying airborne dispersal routes of pathogens over continents to safeguard global wheat supply. *Nature Plants* **3**: 924–929.

*All research references have been subject to peer-review

Competitive funding secured
2004-2010 BBSRC Professorial Fellowship: Disease in changing agricultural environments. BBSRC GBP500,000.
2012 - 2024 Epidemiological modelling to inform strategies for: (i) detection, management and inoculum reduction of wheat stem rust; (ii) monitoring and management of current and emerging cassava virus strains, Bill and Melinda Gates Foundation, GBP3,917,818 – original amount, with two supplements (USD1.5M (2019-21) and USD3.2M (2020-24)
2015 – 2019 Framework agreement for qualitative modelling standing capacity, UK Department for Environment, Food and Rural Affairs (DEFRA), GBP360,000
2016 – 2017 Modelling the spread of Huanglonbing (HLB) disease of citrus in California utilizing the Cambridge modelling interface and Texas HLB data, United States Department of Agriculture Animal and Plant Health Inspection Service (USDA APHIS), USD161,978 (GBP123,647)
2017 – 2019 Real-time and seasonal forecasting of wheat rust epidemics to inform surveillance and control: Ethiopia as an LMIC test case, BBSRC GCRF, GBP276,385

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

1) Forecasting wheat rust diseases in Ethiopia for smallholder farmers to enable timely action

The models for spore dispersal of wheat rust have been used in 2015/16 to produce an early warning system (EWS) in Ethiopia, forecasting up to seven days in advance. Wheat is an important crop in the country, with 5.3M tonnes produced in 2019 (Food and Agriculture Organisation of the UN, crop data). Deployment of the EWS was conducted in partnership with the Ethiopian Agricultural Transformation Agency (ATA), the Ethiopian Institute of Agricultural Research (EIAR), the International Maize and Wheat Improvement Centre (Ethiopia), and the UK Met Office. It successfully provided timely information to assist policy makers (EIAR, the Ethiopian Ministry of Agriculture and Livestock Resources (MoALR), Ethiopian ATA, the International Maize and Wheat Improvement Centre (CIMMYT)) to formulate decisions about allocation of limited fungicide stocks during the 2017 and 2018 seasons. Alerts and advisories were sent by SMS and reports to development agents and smallholder farmers, who rely on wheat for subsistence and livelihood security, enabling them to deploy fungicides to control the disease. The framework represents one of the first advanced crop disease EWSs implemented in a developing country [E1]. The Senior Program Officer for Agricultural Development at the Bill and Melinda Gates Foundation (BMGF), which has supported Prof. Gilligan's work since 2012, describes the EWS as "innovative" and says that prior to its introduction "many growers had…suffered from significant loss". [E2]

A statement from [text removed for publication], who co-fund activity in this region, says that the EWS "is highly effective [text removed for publication] " [E3]

2) Predicting the spread and options for control of cassava brown streak disease in East, Central and West Africa

According to the West African Virus Epidemiology (WAVE) programme, cassava is a major staple food crop for an estimated 500M people in Sub-Saharan Africa. Cassava brown streak virus (CBSV), a major threat to cassava production across the African continent, is spread by an insect vector and the movement of planting material through trade. There are currently no CBSV resistant varieties of cassava available (E2) and the virus can reduce yields by between 50-100% (UN FAO, Food Chain Crisis Early Warning Bulletin, 2018).

As technical partners to WAVE, Prof. Gilligan's group predicted the spread of CBSV through Central Africa, successfully identifying the location and timing of invasion into Zambia and the Democratic Republic of Congo in 2018-19. WAVE has been implemented in ten countries (Benin, Burkina Faso, Cameroon, Côte d'Ivoire, DRC, Gabon, Ghana, Nigeria, Togo and Sierra Leone) with a combined population of 400 million (World Bank, 2019 data). The programme's Executive Director says that Prof. Gilligan has been "instrumental in informing governments of the risks and in instituting surveillance programmes for early warning of the arrival of the pathogen…[and] undoubtedly influential in focussing governments to develop an integrated programme for surveillance, preparedness and response to the disease. This has influenced policies in all ten countries and would not have been possible without the scientific work of the Cambridge team". [E4] In December 2018, government Ministers of Agriculture or Scientific Research from these countries signed response plans to cassava viral diseases, now being implemented with support from WAVE. The Senior Program Officer for Agricultural Development at BGMF states: "Predictions and models [from] the Cambridge team…have been instrumental tools in…mobilizing ministers…to support an integrated program. The models are integral to screening strategies for management of the disease." [E2]

3) Strategy for the control of banana bunchy top virus for the Australian banana industry
Banana bunchy top virus (BBTV) is regarded as one of the most significant disease threats to banana crop production. The disease kills the banana plant within a year and epidemics can lead to complete crop loss if unchecked (CABI Invasive Species Compendium, Banana bunchy top virus data sheet 2019). It is of major concern in Australia, with production in the principal growing region of Northern Queensland forming 70% of the country's AUD605M industry. [E5]

In 2017-18, at the request of Hort Innovation, a grower-owned corporation for Australia's horticulture industry, the Gilligan group successfully developed and tested a model, comparing different scenarios for inspection and detection of disease.

The results showed that an intended change in strategy, switching reliance from trained personnel to growers, would risk a significant build-up of disease in Southern Queensland and Northern New South Wales, where it is endemic. This would negatively affect production in those areas, but also create a greater source of risk for spread into Northern Queensland. The Research and Development Manager at Hort Innovation says the modelling "was clearly explained by Prof. Gilligan and…was undoubtedly instrumental in changing practice, [and] setting targets for surveillance and management to reduce the risk of further spread of the disease." [E5]

4) Surveillance and management strategies for risks to UK woodland trees and citrus trees in the US
Prof. Gilligan previously chaired a UK taskforce on plant disease, and subsequently his group was awarded a competitive commission by Defra to provide the UK Government with a standing capacity for modelling support to inform responses to and preparations for invasions and spread of plant pest and pathogens, from 2016 to 2019. The Chief Plant Health Officer at Defra says that the group has "made a vital contribution to supporting plant health in the UK between 2013 and 2020" and has "enabled Defra to lead the way in the use of epidemiological models and predictions to communicate risk and compare strategies for management of tree disease with stakeholders" [E6]. Specific examples of this are:

a. Dieback disease of ash (*Hymenoscyphus fraxineus*)
There are approximately 185 million ash trees in the UK, fulfilling important roles in supporting biodiversity and ecological functions, which no single alternative UK native tree species can provide. Defra estimates the social and environmental value of ash at over GBP230 million per year, and The Woodland Trust estimates that dieback will kill around 80% of ash trees across the UK without intervention. The work of the Cambridge group successfully demonstrated that,

contrary to current opinion, importation of infected trees for planting was not the only source of infection. Their models were used to inform ministerial decisions on strategies such as the imposition of an import ban for the management of the disease. [E6]

b. Ramorum disease of larch (*Phytophthora ramorum*)
This disease was first identified in UK trees in 2010. Defra was required to provide advice to landowners on management involving removal of infected and surrounding Japanese larch trees, widely grown in the UK. Models from Cambridge were used to provide optimal guidance for the extent of these removals, many of which were statutorily prescribed. The models have been central in a programme from 2014 onwards. [E6]

c. Oak Processionary Moth
This pest of oak trees, accidentally introduced to England in 2005, also causes a harmful rash in humans; it is established in most of Greater London and in some surrounding counties. The Cambridge group provided the Forestry Commission with a set of surveillance plans based upon estimates from epidemiological models for the spread of the pest. These have improved the effectiveness of the surveillance in three successive years (2017-2020) and the identification of caterpillar nests for removal. [E6]

d. Citrus greening disease
Citrus greening disease is threatening the productivity of the citrus industry in California, which covers over 131,000 hectares, and has an annual value of USD3.84B. Prof. Gilligan was commissioned in 2015 by the Animal and Plant Health Inspection Service (APHIS) of the United States Department of Agriculture (USDA) to model the spread of the insect vector and disease. A Quantitative Analyst/Entomologist at the USDA says that the outputs have "been invaluable in informing policy advice by the USDA and the California Department of Food and Agriculture for the surveillance, preparedness and management". These agencies have an annual spend of USD40M per annum in California for such activities. [E7] The disease had already caused a >75% drop in productivity in Florida, and the management programmes implemented using the outcomes of Prof. Gilligan's modelling are designed to prevent similar losses in California. The California citrus industry generates approximately 21,674 full-time equivalent jobs (Babcock, 2018), and work from the Cambridge group has enabled authorities "to avert a potential agricultural disaster that would impact on farm owners and farm workers" [E7]

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

E1. Allen-Sader, C., Thurston, W., Meyer, M., Nure, E., Netsanet Bacha, Alemayehu5, Y., Stutt, R. O., Safka, D., Craig, A. P., Eshetu Derso, Burgin, L. E., Millington, S. C., Hort, M. C., Hodson, D. P., Gilligan, C. A., (2019). An early warning system to predict and mitigate wheat rust diseases in Ethiopia. *Environmental Research Letters,* 14:115004, doi: 10.1088/1748-9326/ab4034
E2. Letter from Bill and Melinda Gates Foundation
E3. [text removed for publication]
E4. Letter from Executive Director of West African Virus Epidemiology (WAVE) programme
E5. Letter from Research and Development Manager at Hort Innovation Australia
E6. Letter from Chief Plant Health Officer at DEFRA
E7. Letter from Quantitative Analyst/Entomologist at the Animal and Plant Health Inspection Service (APHIS) of the United States Department of Agriculture (USDA)