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Forecasting the risk of late blight spread

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SUMMARY

Exposure experiments were conducted to assess the effect of solar radiation on the viability of detached *Phytophthora infestans* sporangia, and the probability of spore survival was analysed as a binary response using a binomial Generalized Linear Mixed Model (GLMM). Receiver operating characteristic curve (ROC) analysis and cross-validation were used to evaluate the global performance of the model for discriminating between viable and non-viable sporangia in the data. The model yielded an area under the ROC curve of 0.92 (95% CI = 0.90–0.93), signifying an excellent classification algorithm. The model was then tested as a forecasting system for potato late blight outbreaks using multiple years of outbreak data from across Great Britain, and achieved a prediction accuracy of 89% with an alert frequency of 1 in 7 days.

KEYWORDS

Inoculum, spore survival, *Phytophthora infestans*, disease risk, decision support system

INTRODUCTION

Solar radiation can have a major impact on the viability of detached (i.e., dispersing) fungal and oomycete sporangia, and thus the risk of between-field spread of disease (Bashi & Aylor, 1983, Belmar-Diaz et al., 2005, Kanetis et al., 2010, Mizubuti et al., 2005, Mizubuti et al., 2000, Olanya et al., 2011, Rotem et al., 1985, Sunseri et al., 2002, Wallin, 1953, Wu et al., 2000). The goals of this study were to: (1) quantify the effects of solar radiation dose on the viability of detached *P. infestans* sporangia belonging to the predominant genotypes in Great Britain (GB), (2) derive a simple binary classification model for predicting viable versus non-viable inoculum, and (3) validate the model as a tool for forecasting late blight outbreaks using 10 years of national-scale outbreak data from across GB.

MATERIALS AND METHODS

P. infestans sporangia of four different isolates belonging to the two predominant genotypes in GB (2 × 13_A2, and 2 × 6_A1) were exposed to ambient conditions at the James Hutton Institute, Dundee, Scotland (56°27'24.6"N and 3°04'10.2"W) between July and September 2016. The experiment was conducted on seven different days with exposures lasting 0, 1, 2, and 3 hours, at different times of the day. Sporangia were harvested by gently pressing lesions onto round, 47mm diameter, 0.45μm pore, mixed cellulose esters membrane filters. The filter papers were attached to a screen comprised of muslin cloth connected to a wooden frame. The cumulative dose of solar (direct and diffuse) radiation received during exposure was determined using a Kipp & Zonen CMP3 Pyranometer, sourced from Campbell Scientific. Following exposure, the filter papers were removed from the screen and placed into a moist chamber to allow slow rehydration. Sporangia on filters were then transferred to water agar (1.5%) in petri-dishes and incubated at 18°C in the dark. Germination assessments were made after 24 h of incubation by counting at least 300 sporangia per replicate under a microscope (100x) and recording the number that had germinated or not. No distinction was made between direct or indirect sporangial germination.

A Generalized Linear Mixed Effects Model (GLMM) with a binomial distribution and a logit link function was used to estimate the probability that sporangia would be viable (germinate) based on the cumulative solar radiation dose during exposure. Our primary interest, however, was in developing a binary classification model in which the outcomes are labelled as positive or negative, or in this study, as viable or non-viable sporangia. In order to do so, the quantitative predictions (estimated probabilities of spore survival) of the model had to be converted to qualitative 'viable' and 'non-viable' labels. This required setting a 'decision threshold' or a 'cut-off value,' i.e., an estimated probability of survival above which sporangia were classified as viable, and below which sporangia were classified as non-viable. Receiver operating characteristic (ROC) analysis was used to evaluate the performance of the model as a binary classification system; an ROC curve was created by plotting the proportion of sporangia that were correctly classified as viable against the proportion that were misclassified as viable, for every possible cut-off value. To test the robustness of model predictions, the model was trained and tested using 10 repeats of 10-fold cross-validation. The accuracy of the model as a binary classification system was evaluated based on the area under the ROC curve (AUC), and a variety of statistical techniques were used to determine the optimal cut-off point for correctly classifying viable and non-viable sporangia.

The ability of the classification model to forecast the risk of between-field spread of disease was tested using historical late blight outbreak data from the AHDB Potatoes 'Fight Against Blight' campaign; these data comprised almost 2000 outbreaks from across GB, spanning 2005-2014. The model was driven using 1 km gridded solar radiation data (W m^{-2}) from the Climate hydrology and ecology research support system meteorology dataset for Great Britain (1961-2015) [CHESS-met]. A 28 day period prior to the date that each outbreak was reported was considered to be sufficient for relating weather conditions for survival of dispersing inoculum to the dates at which disease was first observed in the crop. On each day in that 28 day period, the classification model was used to 'forecast' if inoculum would be viable or non-viable. A prediction of viable inoculum on any day in that 28 day period was considered a successful forecast of that outbreak in this analysis. The number of forecasts in each 28 day period was calculated to determine the overall frequency of alerts.

RESULTS

We considered pathogen isolate as a grouping variable, but it did not have a significant effect on the probability of germination, nor on the relationship with radiation dose. The fixed effects portion of the final GLMM can be used to compute the model-based probability, *P* (on a continuous scale ranging from 0 to 1), of spore viability for a given cumulative solar radiation dose, x: $P = 1 / (1 + \exp(-(2.37 - 0.45x)))$. The mean AUC (area under the empirical ROC curve) value of the model under the 10 × 10-fold cross-validation technique was 0.92 (95% CI = 0.90–0.93), signifying an excellent overall performance in discriminating between viable and non-viable sporangia in the experimental data (Figure 1). The best-performing cut-off (estimated probability) value for correctly classifying viable and non-viable sporangia was the point that minimised the straight line distance between the ROC curve and the upper left corner of the unit square, which is the point of perfect prediction: $P = 0.60$ (Figure 1). This resulted in an accuracy of 0.83 (95% CI = 0.82–0.85) in classifying sporangia in the experimental data.

The number and geographic distribution of potato late blight outbreaks varied greatly between years, ranging from 66 to 288 outbreaks, with a mean value of 182 outbreaks per year. The 'blight season' typically started in May, peaked in July, and ended in September. The binary classifier was able to correctly forecast 88.9% of outbreaks (mean value across all years) with a corresponding frequency of alerts of approximately 1 in 7 days classified as risk periods for between-field spread of disease (Figure 2). The mean length of time between the first alert in each 28 day window and the date at which disease was first observed and reported was 13.7 (SD±4.5) days.

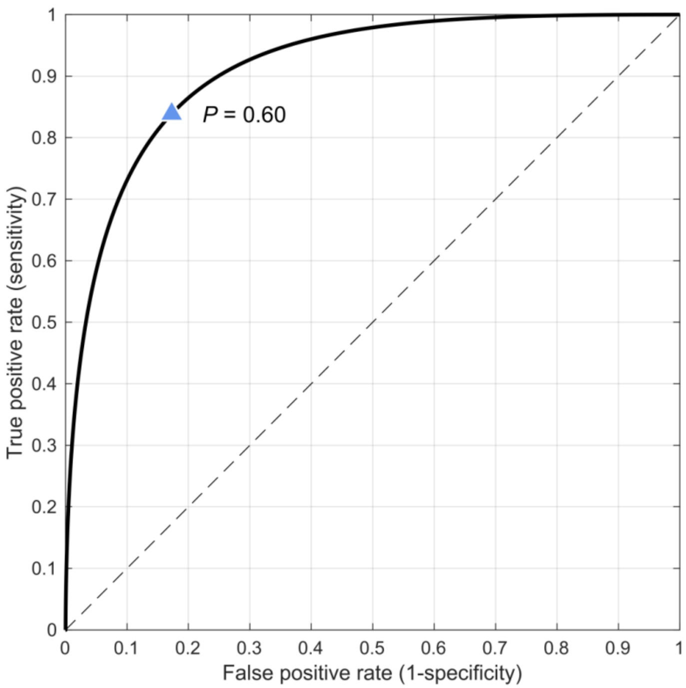

Figure 1. *Receiver operating characteristic (ROC) curve of the model for classifying spore survival outcome. The data marker shows the optimum cut-off probability value (P = 0.60) for classifying inoculum as viable or non-viable in the model. The model yielded an AUC of 0.92 (95% CI = 0.90–0.93)*

DISCUSSION

In this study we derived a simple logistic model for predicting the probability that detached (dispersing) *P. infestans* inoculum will remain viable after exposure to solar radiation. An important aspect of this model is the subsequent ease of computation; it requires only the cumulative dose of solar radiation as input, and it can be used with the aid of a basic calculator to predict the probability, P, of spore survival on a continuous scale ranging from 0 to 1. We also identified $P = 0.60$ as the optimum cut-off value for classifying sporangia as viable or non-viable in the experimental data. In this study we further extended our analyses beyond the norm for dose-response studies in aerobiology, which tend to focus solely on derivation of a dose-response curve or classification algorithm, and validated the binary classifier as a tool for forecasting outbreaks of disease using 10 years of national late blight outbreak data from across GB. The model achieved a predictive accuracy of 88.9% in forecasting late blight outbreaks, with a frequency of one risk alert per week. Although other meteorological risk factors could have been considered to improve the model, e.g., temperature and humidity, our goal was not to derive a comprehensive model of the environmental conditions underlying the survival of detached sporangia, but to produce a simple model that is both useful to and useable by growers and other practitioners in the agricultural sector. The resultant classifier could be easily integrated into existing decision support systems (DSS) for potato late blight that are currently implemented across Europe. To our knowledge, none of the widely adopted DSSs in Europe include any estimation of the risk of between-field spread of disease, and instead operate under the assumption of ubiquitous, viable inoculum throughout the season, and typically utilise a set of temperature and humidity rules to forecast the risk of infection (Cooke et al., 2011, Hansen, 2014). As our classifier for spore survival was derived using data on the predominant *P. infestans* genotypes in GB and Europe (13_A2 and 6_A1), it would serve as a useful complement to these systems, providing a binary (yes or no) forecast of the risk of between-field spread of disease that could be used to modify spray recommendations based on infection conditions only.

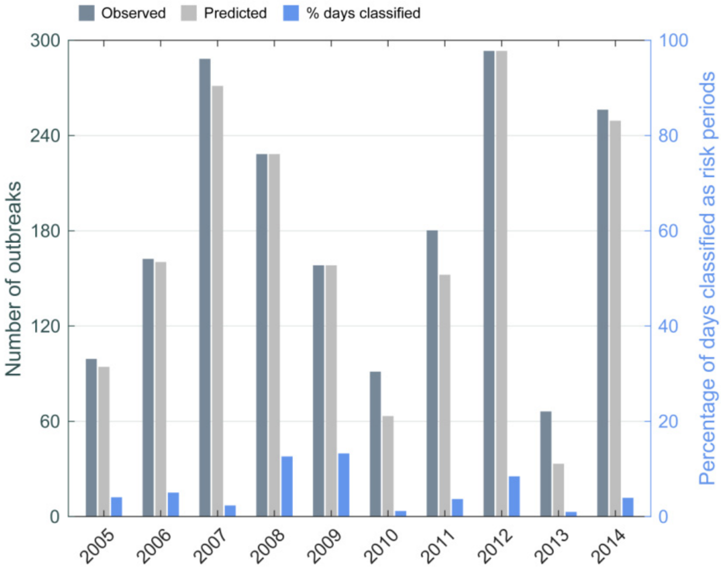

Figure 2. *Accuracy and frequency of forecasts of potato late blight risk using the binary classification model for spore survival. Dark grey bars show the number of observed late blight outbreaks each year, light grey bars show the number of outbreaks that were correctly forecast by the model, and blue bars show the percentage of days that received a risk warning.*

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