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Monitoring invasive pathogens in plant nurseries for early-detection and to minimise the probability of escape

Vasthi ALONSO CHAVEZ [a,*], Stephen PARNELL [a,b], Frank VAN DEN BOSCH [a]

[a] Department of Computational and Systems Biology, Rothamsted Research, Harpenden, AL5 2JQ, UK
[b] University of Salford, School of Environment and Life Sciences, Manchester, M5 4WT, UK

HIGHLIGHTS

- We develop monitoring and tracking strategies for plant epidemic in nurseries.
- We account for the asymptomatic periods of disease development.
- Developing programmes for epidemic early-detection is possible.
- Once a disease is detected, tracking it onwards is most likely needed.

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ABSTRACT

The global increase in the movement of plant products in recent years has triggered an increase in the number of introduced plant pathogens. Plant nurseries importing material from abroad may play an important role in the introduction and spread of diseases such as ash dieback and sudden oak death which are thought to have been introduced through trade. The economic, environmental and social costs associated with the spread of invasive pathogens become considerably larger as the incidence of the pathogen increases. To control the movement of pathogens across the plant trade network it is crucial to develop monitoring programmes at key points of the network such as plant nurseries. By detecting the introduction of invasive pathogens at low incidence, the control and eradication of an epidemic is more likely to be successful. Equally, knowing the likelihood of having sold infected plants once a disease has been detected in a nursery can help designing tracing plans to control the onward spread of the disease. Here, we develop an epidemiological model to detect and track the movement of an invasive plant pathogen into and from a plant nursery. Using statistical methods, we predict the epidemic incidence given that a detection of the pathogen has occurred for the first time, considering that the epidemic has an asymptomatic period between infection and symptom development. Equally, we calculate the probability of having sold at least one infected plant during the period previous to the first disease detection. This analysis can aid stakeholder decisions to determine, when the pathogen is first discovered in a nursery, the need of tracking the disease to other points in the plant trade network in order to control the epidemic. We apply our method to high profile recent introductions including ash dieback and sudden oak death in the UK and citrus canker and Huanglongbing disease in Florida. These results provide new insight for the design of monitoring strategies at key points of the trade network.

1. Introduction

Nurseries are businesses where plants and trees are planted, grown and/or traded to be used in different industry sectors such as gardening, forestry and conservation. Different nurseries specialise in different phases of the commercialisation process, ranging from seed production to propagation, plant growth and plant sale at different scales.

Trade globalisation has enabled the movement of plant material between countries and continents. Trade of plants and plant products between nurseries within the same region and across countries has become a regular activity. However, this trade has increased the exposure of plants inside and outside the nursery to new pest and diseases. This has facilitated the introduction of invasive plant pathogens at unprecedented levels (Dehnen-Schmutz et al., 2010; Hulme, 2009; Liebhold et al., 2012) with significant

* Corresponding author.
E-mail address: vasthi.alonso-chavez@rothamsted.ac.uk (V. ALONSO CHAVEZ).

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ecological (Boyd et al., 2013) and agricultural (Strange and Scott, 2005) consequences, threatening the profitability of the plant trade industry, the sustainability of ecosystems and the survival of a number of tree and plant species.

Examples include the spread of sudden oak death, caused by *Phythophtora ramorum* in North America and Europe (Grünwald et al., 2012) with disastrous ecological impact, the introduction of Citrus Canker and Huanglongbing disease caused by *Xanthomonas axonopodis* and *Diaphorina citri* respectively in Florida (Gottwald, 2010; Gottwald et al., 2002a), diseases that threaten the survival of the citrus industry in that state. A more recent example indicates that ash dieback, a fungal disease affecting ash trees across Europe, may have been introduced into the UK through nursery trade, among other sources of spread (Woodward and Boa, 2013). Being ash a keystone tree species in Europe, this disease threatens European biodiversity as well as the forestry industry and ecosystem services (Pautasso et al., 2013).

The detection of infected material can be challenging as infected plants often show no symptoms of the disease for a period of time (i.e. they have an asymptomatic period). This means that, even the most rigorous visual inspections are unlikely to detect all arriving infected hosts (Liebhold et al., 2012).

Developing strategies to monitor and control the spread of diseases in order to detect and trace invasive plant pathogens at low incidence in different points of the nursery production chain is needed. Effective monitoring is a fundamental tool to reduce the costs associated with the eradication and control of plant diseases.

To help inform effective monitoring methods we develop a model to monitor a nursery where a plant pathogen may be introduced. We consider two key questions:

1. How frequent and how much do we need to sample to detect the pathogen at low incidence in the nursery? Using a simple epidemiological model, we calculate the expected incidence at first discovery, the discovery-incidence. Previous studies have addressed how a monitoring programme determines the incidence at first discovery (Parnell et al., 2012) and the time to first discovery (Metz et al., 1983) but the influence of an asymptomatic stage has never been addressed and is a key issue for plant diseases.
2. What is the probability that, given a monitoring programme and intensity, plants have been sold from the nursery before the epidemic is discovered? This is important in the development of tracking and control strategies in a trade-network and has not been addressed in previous studies.

In the model, we consider that the population is divided into susceptible, asymptomatic infected and symptomatic infected plants. In this way we incorporate the time that a host takes to develop symptoms from the moment it is infected.

We analyse the effect of frequency and intensity of plant sampling and selling, as well as the effect of epidemic growth rate and asymptomatic periods on the discovery-incidence and on the probability that infected plants having been sold from the nursery before a disease is detected. We apply our methods to analyse the cases of ash dieback, sudden oak death, citrus canker and Huanglongbing disease.

In human and animal epidemiology, disease incidence measures the rate of occurrence of new cases of a disease or condition in a specified time, whereas disease prevalence gives a measure of how many individuals are diseased at a single point in time (Shields and Twycross, 2003). In plant epidemiology however, disease incidence is usually defined as the number of plant units that are diseased as a percentage of the total number of sampled units, whereas disease prevalence measures the proportion of geographical sampling units where a disease has been found to occur divided by the total number of geographical sampling units sampled (Madden et al., 2007; Nutter et al., 2006). Here, we adopt the plant pathology terminology and use the term disease incidence to characterise the proportion of individuals infected from the total host population.

2. Model and methods

In this section we present an epidemic model for the invasion of a pathogen in a plant nursery. We develop a numerical method and an analytical approximation to calculate:

(1) The incidence an epidemic has reached when it is detected in the nursery for the first time (i.e. discovery-incidence).
(2) The probability that no infected plants have been sold from the nursery before the epidemic is detected for the first time.

2.1. Epidemic in the nursery

We consider a scenario where a disease is introduced in a plant nursery where a monitoring programme is in place and plants are being sold at regular intervals of time. Once the disease arrives in the nursery, we assume that the disease epidemic follows logistic epidemic growth (Metz, 1978; Segarra et al., 2001).

Infected plants initially show no symptoms but after some time λ develop visible symptoms and the epidemic can be detected through inspection. The population of infected plants thus is composed of asymptomatic and symptomatic individuals. Considering this, we write the incidence of infected plants at the discovery time t_1, as total $q(t_1)$ (including symptomatic and asymptomatic individuals) and symptomatic $q_S(t_1)$ (Fig. 1).

In contrast with, Parnell et al. (2012) who introduce their approximation from a set of ODE's and the relation with the exact stochastic problem was not proven, we derive the approximation directly from the stochastic model. The logistic function for the total incidence $q(t)$ at time t, (*i.e.* the sum of the symptomatic and asymptomatic incidences) can be written as

$$q(t)=\frac{q_0\cdot e^{r(t-t_0+\lambda)}}{1-q_0+q_0\cdot e^{r(t-t_0+\lambda)}}, \quad (1)$$

and the incidence of the symptomatic incidence as

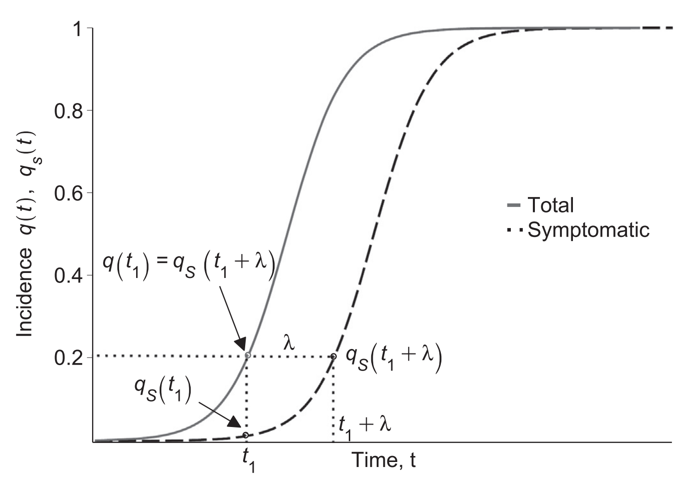

Fig. 1. The epidemic incidence grows logistically over time with a fixed growth rate. The incidence is divided in total and symptomatic. The symptomatic incidence at t_1, $q_S(t_1)$ is smaller than the total incidence $q(t_1)$ at the same time. In general, the total incidence at any given t_1 is the incidence of the symptomatic population at $t_1+\lambda$, *i.e.* $q(t_1)=q_S(t_1+\lambda)$.