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Modelling the impact and control of an infectious disease in a plant nursery with infected plant material inputs

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ABSTRACT

The ornamental plant trade has been identified as a key introduction pathway for plant pathogens. Establishing effective biosecurity measures to reduce the risk of plant pathogen outbreaks in the live plant trade is therefore important. Management of invasive pathogens has been identified as a weakest link public good, and thus is reliant on the actions of individual private agents. This paper therefore provides an analysis of the impact of the private agents' biosecurity decisions on pathogen prevention and control within the plant trade. We model the impact that an infectious disease has on a plant nursery under a constant pressure of potentially infected input plant materials, like seeds and saplings, where the spread of the disease reduces the value of mature plants. We explore six scenarios to understand the influence of three key bioeconomic parameters; the disease's basic reproductive number, the loss in value of a mature plant from acquiring an infection and the cost-effectiveness of restriction. The results characterise the disease dynamics within the nursery and explore the trade-offs and synergies between the optimal level of efforts on restriction strategies (actions to prevent buying infected inputs), and on removal of infected plants in the nursery. For diseases that can be easily controlled, restriction and removal are substitutable strategies. In contrast, for highly infectious diseases, restriction and removal are often found to be complementary, provided that restriction is cost-effective and the optimal level of removal is non-zero.

1. Introduction

Increases in the movement of people and traded goods as a consequence of globalisation have led to growing concerns about the threat posed by invasive species. especially invasive pathogens of humans, plants and animals (e.g. Anderson et al., 2004; Waage and Mumford, 2008; Perrings et al., 2010; Hulme, 2014; Dalmazzone and Giaccaria, 2014). Recent disease outbreaks in plants, such as the Chalara fungus (*Hymenoscyphus pseudoalbidus*) affecting ash trees across Europe (Pautasso et al., 2013) and the oomycete *Phytophthora ramorum* affecting many plants including larch in Europe (Brasier and Webber, 2010) and oaks in the US (Rizzo et al., 2002), have focused attention on the policy options to reduce the risks of similar plant disease outbreaks occurring in the future, and the management options to reduce damage from newly established pathogen populations. These disease outbreaks have also raised concerns about patterns of plant trade, which has been identified as a key introduction pathway for invasive pathogens (Santini et al., 2013), and on the need for a more prominent role of the private sector in biosecurity practices to mitigate existing risk (Liebhhold et al., 2012). Understanding the economic impacts of damage and mitigation is essential for determining optimal policy and management options for invasive pathogens (Stohlgren and Schnase, 2006).

The body of the literature that combines invasion ecology with economic analysis to deal with these issues has drastically increased in the last decade (for an overview see Olson, 2006; Marbuah et al., 2014). Bioeconomic studies explore the management problem from a central authority perspective, focusing on the potential social welfare benefits from policy intervention to limit the risk of invasive species

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damages using instruments that include port inspections, quarantine and import tariffs (McAusland and Costello, 2004; Mérel and Carter, 2008), import risk screening programmes (Keller and Springborn, 2014; Springborn et al., 2015), the use of public funds to detect, eradicate and/or control established invaders, and habitat restoration (e.g. Olson and Roy, 2002; Mehta et al., 2007; Sims and Finnoff, 2013). Other studies have examined the trade-off between preventive measures before the arrival and control measures after the invader is known to be in the country in order to determine the optimal allocation of limited public resources between these two strategies (e.g. Leung et al., 2002, 2005; Finnoff et al., 2005, 2007; Haight and Polasky, 2010; Sanchirico et al., 2010) Here we add to this literature by adopting a private sector perspective, in order to understand the biosecurity vulnerability and management incentives affecting individual businesses.

One of the challenges for developing policy to reduce the risk of outbreaks of pathogens is the fact that the potential routes of invasion are not only diverse, but also that they are controlled by a mixture of public and private agents. Trading decisions made by private decision-makers may have significant implications for public interest at a regional or national level, but the public costs of an outbreak are likely to far exceed the costs experienced by any one private business, and a privately optimal trading decision is very unlikely to match the publicly optimal one due to potential conflicting interests (Perrings et al., 2005; Mills et al., 2011). Effective control of the risk posed by invasive pest and diseases has been defined as a ‘weakest-link’ public good (e.g. Perrings et al., 2002; Burnett, 2005). Therefore, the risk of outbreak can be in the hands of a single private firm in the trading network. This can limit the level of success of decentralised biosecurity efforts, although it may also allow the firm to take a leadership role, creating incentives for other firms to take action (Hennessy, 2008).

This paper studies the relationship between prevention and control strategies in the context of plant trade. We take a single nursery perspective in order to understand the biosecurity vulnerability and incentives affecting private firms, that can inform subsequent analysis on networks and policy development. We develop a simple bioeconomic model of a private nursery owner who buys in, grows and sells on plants in the face of the threats posed by an infectious pathogen. The management options available to the nursery owner are some combination of (1) restriction, i.e. prevention measures to reduce the number of infected plant materials coming from input sources (for example, inspecting inputs and/or investigating and discriminating input suppliers based on perceived cleanliness) and (2) removal, i.e. taking out infected plants within the nursery. Other means of management like cleanliness and fungicide use are assumed to at constant optimal levels.

Prior bioeconomic research on the plant trade has focused on its role as a significant pathway to the introduction of potentially exotic invasive plants, exploring the use of taxes or annual license fee to reduce this risk and cover the expected environmental damages (Knowler and Barbier, 2005; Barbier et al., 2011). However, implementing these market-based instruments is challenging due to the lack of support among stakeholders in the industry (Barbier et al., 2013; Touza et al., 2014). In this paper, we follow current research on private biosecurity responses to livestock diseases, where disease risk does not only depend on agents’ choices but also is characterised by an underlying epidemiological dynamics (Horan et al., 2010). In this framework, (Horan and Fenichel, 2007) are concerned on the management problem characterised by livestock-wildlife interactions in disease transmission; and (Gramig and Horan, 2011) studied the role of government policies as regular testing on encouraging farmers’ biosecurity investments. More recently, (Horan et al., 2015) focused on assessing whether trade always increase risk or whether it can act as a disease management mechanism.

Our focus, however, is the threat associated with private trading decisions, as infected goods can be bought in and sold on. We contribute to the above work by focusing on plant trade, and addressing the role of both private preventing and controlling behaviour to limit disease transmission risk characterised by epidemiological dynamics. Thus, we examine the potential trade-offs and synergies between these management decisions when the nursery owner’s objective is to minimise the expected private costs from infection management and revenue losses associated with the reduced value of infected plants. We find that if the disease spreads faster than the ability to control the disease, removal and restriction complement each other whereas if the disease is controllable, removal and restriction become substitutes.

2. Model derivation

2.1. Disease dynamics

We consider a plant nursery with a nursery owner who constantly buys plant material, grows it and sells it on when the plant becomes mature (i.e. reaches a target age). A disease is introduced within the input plant material and spreads within the nursery. For simplicity and generality, we assume that the plant population is split into two classes, susceptible plants (S) and infected plants (I). Infected plants can infect susceptible plants, and once infected a plant remains infected for the rest of its time in the nursery; there is no recovery from the infection.[1] The consequence of infection for the nursery owner is that infection alters (assumed here to reduce) the net price obtained from selling of a mature plant.

To combat the spread of the infection within the nursery, the nursery owner has two different control measures. The owner can invest (i) in **restriction** to reduce the proportion of infected inputs (be it from inspecting inputs and rejecting infected plants or by selecting suppliers with less infected material); and (ii) in the **removal** of infected plants within the nursery. Removal reduces the time an infected plant stays in the nursery, avoiding additional secondary invasions, but provides no revenue.

Schematically, the plant-disease dynamics can be described as (see Fig. 1):

Change in S = Input of S − Output of S − Disease Transmission,
Change in I = Input of I − Output of I − Removal of I + Disease Transmission.

For simplicity, we assume that the stock of plants at the nursery is fixed, N, which may mean for example that the nursery is always full (this is a simplifying assumption that is not necessarily realistic; we address this in Section 4). To do this, we set Total Input = Total Output + Removal, where Output of $S = \delta S$ and Output of $I = \delta I$, where δ is the rate of plants become mature and sold off (i.e. plants stay

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[1] Although there is no recovery, infected plants can leave the system via being sold on or being removed and be replaced by a susceptible plant. This means there is some kind of pseudo-recovery, meaning the system behaves more like a classic SIS system than SI.