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Analysis

A practical optimal surveillance policy for invasive weeds: An application to Hawkweed in Australia

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ABSTRACT

We propose a practical analytical framework which can help government agencies determine an optimal surveillance strategy for invasive weeds, including cases of slow-growing or ‘sleeper weeds’, and for all weeds at early stages of invasion where quantitative information is scant or rough. The framework consists of three key components: (a) a simple rule that can determine weed surveillance zones or where early detection is desirable, (b) a function that maps surveillance effort to early detection probability, and (c) a schedule to determine an optimal surveillance budget. A calibration to Hawkweed in Australia provides an example of the framework and shows that the optimal annual surveillance budget for this sleeper weed is substantial.

1. Introduction

The damage from ‘invasive alien species’ (IAS), including exotic weeds, pests and diseases, is widely acknowledged. Costing not only billions of dollars every year in agricultural and environmental losses (European Commission, 2008; Pimentel et al., 2005; Sinden et al., 2005), damages to biodiversity are, in some cases, irreversible (Gurevitch and Padilla, 2004; Vitousek et al., 1996; Wilcove et al., 1998). These damages are often, in fact, underestimated due to the lack of a suitable demand function that accurately reflects the value of ecological services (Costanza et al., 1989; Hester et al., 2006). Progress in achieving a significant reduction in the rate of biodiversity loss due to IAS, to 2010, has clearly been disappointing (Butchart et al., 2010), despite the fact that targets have been incorporated into the United Nations Millennium Development Goals designed to arrest IAS-related biodiversity loss.

Preventing the introduction of IAS at the border, or pre-border, has been considered a first-line of defence against all bio-invasions (Finnoff et al., 2007; NISC, 2008; Olson and Roy, 2005). However, it is impossible to prevent all such pathways even when, as often is the case, the chance of a successful invasion and establishment may be small (Williamson, 1996). For this reason, local or post-border surveillance for early detection and rapid response, a second line of defence, has recently attracted considerable attention as it increases the likelihood that localised invasive populations will be found, contained, and potentially eradicated before they become more widely established (NISC, 2008). As early detection generally requires substantial upfront investment, while delayed detection can cause otherwise considerable if not devastating damages, there exists a clear trade-off between surveillance expenditures for an invasive species and any potential damage and control costs.

This trade-off has been explored in the literature in a number of different ways. Some authors have stressed the importance of detectability and biological relationships as factors influencing the optimal level of surveillance (e.g. Bogich et al., 2008, Kompas and Che, 2009, Mehta et al., 2007). Others have highlighted the impact of spatial heterogeneity on budget allocation (Hauser and McCarthy, 2009; Homans and Horie, 2011), and the design of optimal long-term strategies with spatial heterogeneity, rather than one-off surveillance programs (Epanchin-Niell et al., 2012). All of these models vary in complexity, and also in terms of the spatial distribution of species and detection probability functions.

Immediate need and effective policy responses often shift the emphasis to more basic models that explore this early detection tradeoff in contexts where biosecurity measures and surveillance

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policies, in particular, are often implemented with imperfect information about the target species, or the many underlying and hard-to-quantify parameters needed for complex modelling. Indeed, difficulties in specifying key parameters, especially those in terms of measures of uncertainty and the variability of model components, are often the main obstacle to obtaining an objective measure of control programs and needed expenditures (Hulme, 2012). For instance, if a model requires detailed habitat suitability maps or a detection probability function that is specified in a particular context, it is likely not relevant for policy makers, simply because the required information is not yet available or too context-specific to apply to new situations in a timely manner.

We propose a simple but practical framework which can help government agencies and other decision-makers to determine a surveillance strategy for invasive weeds. Our model requires only a few, albeit indispensable, parameters which can be collected by policy makers or adopted from other studies where relevant. This is important because quantitative information about a slow-growing weed (also referred to as 'sleeper weeds'), at its early stage of invasion, is often scant or rough, even though the weed may have drawn the attention of both policy makers and the scientific community.

We start our analytical framework in Section 2 with an analysis of the economics of weed eradication from a single entry. The key result of this section is a rule that characterises the difference between containment and surveillance zones. The rule can be applied in any spatially-heterogeneous context, as is often the case with biosecurity measures (Albers et al., 2010; Williamson, 2010), to specify containment zones where eradication is not cost-effective, and hence where there is no need for early detection. Outside the containment zone, termed for our purposes as a 'surveillance zone', where any delays in eradication are costly, and the location of a weed is not known, one may want to allocate more resources to find or detect the weed early.

Section 3 of the paper builds a detection-effort relationship (i.e., a detection probability function) which maps surveillance effort and infestation size to detection probability. While many authors specify a particular function, or an estimated function from a specific context, our approach draws on a simulation based on how surveillance activities are usually implemented. The advantage of the simulation approach is its wider applicability since information on surveillance patterns is often available to policy makers, while the applicability of a specified parametric function is much more limited outside of the specific context where it is estimated.

In Section 4, we analyse the economics of surveillance in the case of sequential entries where a weed can re-enter multiple times. A stochastic programming algorithm is used to determine the optimal surveillance budget which minimises the total cost of the surveillance expenditure itself, the expected eradication expenditure and the pre-eradication loss caused by the weed. In Section 5, the model is calibrated to Hawkweed in Australia, as an example of the approach. Hawkweed is listed as one of 28 non-native invasive weeds that threaten biodiversity and cause other environmental damages in Australia. Many might typically assume that only limited (or no) surveillance is required in the early stages of the establishment and spread of Hawkweed, since it is such a relatively slow-growing weed. This turns out not to be the case. Section 6 concludes.

2. Containment and Surveillance Zones

When it comes to controlling a weed at a particular location and point in time there are two basic options, namely eradication and doing nothing. The costs and benefits of eradication versus doing nothing depend on various factors. One of the conditions that supports eradication is when the spread rate of the weed is larger than the discount rate (Clark, 1976; Fraser et al., 2006; Harris et al., 2001; Olson and Roy, 2002). This is a sufficient condition because it guarantees that the loss will grow at a faster rate than the eradication expenditure, so early eradication is cost-effective. In this section, we will illustrate a broader condition that determines the cost-effectiveness of early eradication even when the spread rate is smaller than the discount rate; a rule that can also help determine the benefit of early detection.

Suppose that we are considering whether to eradicate an existing invasive weed in a land parcel. If not eradicated, for a period of time $[0, T]$, the weed spreads at rate $r > 0$. Let x_0 be the initial entry size. Using a simple exponential formula, typically applied to model the dynamics of an invasive species in the early stages of a biological invasion, the invaded area at time T will be

$$x(T) = x_0 e^{rT} \tag{1}$$

The presence of a weed in a parcel causes losses, including quantifiable losses in agriculture and losses measured by non-market values such as environmental and socio-economic amenities and externalities. We denote d as this annual multi-criteria impact for losses in monetary terms (Cook and Proctor, 2007) caused by the invasion of the land parcel. The present value of the loss from time 0 to T, discounted at annual rate ρ is thus

$$L(T) = \int_0^T [d \times x(t)]\, e^{-\rho t} dt = x_0 \frac{d}{r-\rho}\left[e^{(r-\rho)T} - 1\right] \tag{2}$$

Another cost incurred in a weed control strategy is, when needed, an eradication expenditure. Here, the literature over the relationship between total eradication expenditures and infestation size is mixed. Some authors claim that it may be impossible to eradicate a weed if its infestation is large (Adamson et al., 2000; Harris et al., 2001; Hester et al., 2006), while others show estimates that indicate that eradication expenditures per unit of successfully eradicated land size become smaller as land size increases (Cunningham et al., 2003; Rejmánek and Pitcairn, 2002; Woldendorp and Bomford, 2004). These latter estimates are often biased, however, by the fact that they ignore some basic eradication-feasibility issues, particularly where the possibility of an unsuccessful eradication and the geographical characteristics of an eradication site are not adequately considered or controlled. Some weed specialists also emphasise that the eradication of a large area can often be successful if adequate resources are devoted to it (Panetta and Timmins, 2004; Rejmánek and Pitcairn, 2002; Simberloff, 2003), though the needed expenditure can be very high indeed as seeds can remain hidden in the soil for a long time (Cacho et al., 2006; McArdle, 1990).

With this in mind, we denote the total present value of all costs associated with the eradication of weeds on a land parcel as a finite number c. This may not be a 'one-off' item, but can be a flow of expenditures spent on physical removal, monitoring and other follow-up activities. The eradication expenditure discounted to the time of entry is

$$R(T) = e^{-\rho T} c x(T) = c x_0 e^{(r-\rho)T} \tag{3}$$

The total cost of controlling a known invasion is the sum of the cumulative loss in Eq. (2) and the eradication expenditure in Eq. (3), where both depend on the chosen eradication time T. The effect of the eradication time on the total cost will determine the economic viability of an immediate eradication. If a delay in eradication increases the total cost, it is cost-effective to eradicate the weed immediately. Otherwise, one will choose not to eradicate the weed, at least for a period of time. Summing up the two components for the