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Analysis

There is no silver bullet: The value of diversification in planning invasive species surveillance

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ABSTRACT

In this study we demonstrate how the notion of diversification can be used in broad-scale resource allocation for surveillance of invasive species. We consider the problem of short-term surveillance for an invasive species in a geographical environment. We find the optimal allocation of surveillance resources among multiple geographical subdivisions via application of a classical portfolio framework, which allocates investments among multiple financial asset types with uncertain returns in a portfolio that maximizes the performance and, by meeting the desired diversification targets, protects against errors in estimating the portfolio's performance.

We illustrate the approach with a case study that applies a spatial transmission model to assess the risk of spread of the emerald ash borer (EAB), a significant pest in North America, with infested firewood that may be carried by visitors to campground facilities in central Canada. Adding the diversification objective yields an expected survey performance that is comparable with undiversified optimal allocation, but more importantly, makes the geographical distribution of survey priorities less subject to possible errors in the spread rate estimates. Overall, diversification of pest surveillance can be viewed as a viable short-term strategy for hedging against uncertainty in expert- and model-based assessments of pest invasion risk.

1. Introduction

Invasive alien species are a universally recognized problem, causing significant environmental changes and large-scale economic damages worldwide (Hulme et al., 2008; Mack et al., 2000; Meyerson and Reaser, 2003; Perrings et al., 2005). Most introductions of new species have been linked to human activities such as international trade (Costello and McAusland, 2003; Hulme, 2009; Jenkins, 1996; Levine and D'Antonio, 2003), transportation (Paini and Yemshanov, 2012; Tatem and Hay, 2007) and recreation (Koch et al., 2012). Various post-border surveillance procedures (e.g., Cook and Fraser, 2008; Reaser et al., 2008) have been implemented to detect the arrival of non-native organisms via these and other pathways. For example, in 2007 the United States Department of Agriculture (USDA) allocated $US 1.2 billion for management of invasive species, with approximately 22% directed toward early detection and rapid response activities (NISC, 2007). A considerable portion of such funding is spent on large-scale pest surveillance programs (Tobin, 2008).

A common objective in surveillance programs aimed at early detection is to gain as much information as possible about the extent of a species' presence in its new environment. Typically, surveillance planning requires some understanding of the species' behavior, such as its capacity to spread to new locations. A variety of models that simulate the invasion process have been used to help with the assessment of species spread (Koch et al., 2009; Pitt et al., 2009; Prasad et al., 2010; Yemshanov et al., 2009). Regardless, knowledge about the behavior of a recently discovered pest in a novel landscape is typically poor, such that any estimates of the organism's spread potential can only be stated in vague probabilistic terms (such as likelihood of spread or the probability of arrival at a specified distance). This further complicates

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the planning of pest surveillance because decisions about allocating resources for the surveys have to be made under substantial uncertainty.

1.1. Pest Survey Planning as a Portfolio Valuation Problem

Several methods have been applied to improve the performance of pest surveys, such as identifying surveillance protocols that are robust to uncertainty (Leung et al., 2010; Moffit at al., 2008), applying cost-minimization studies (Sharov and Liebhold, 1998; Hester et al., 2013), assessments of "wait and see" strategies (Sims and Finnoff, 2013) and optimal allocations of search protocols (Epanchin-Niell et al., 2012; Hauser and McCarthy, 2009; Hester and Cacho, 2012; Mehta et al., 2007). In this study we conceptualize the short-term allocation of pest surveillance resources as a portfolio valuation problem. Portfolio theory has been used to allocate investments in financial assets under uncertainty (Elton et al., 2010). In classical portfolio theory, the primary decision problem is to determine the allocation of investments among *m* asset types with uncertain returns in a portfolio that maximizes the net returns and protects the investments against volatilities (i.e., the variance of the net return values, which serves as a measure of financial risk). Modern portfolio theory also emphasizes the balancing and diversification of investment assets as measures that reduce the risk of unexpected financial losses (Elton et al., 2010).

While the portfolio allocation problem has been covered extensively in the financial literature, few studies have considered geographical applications of the approach, particularly for tasks such as the surveillance of invasive species (although see Prattley et al., 2007 for similar applications in animal health control). In this study, we consider the general case of survey planning for a recently discovered invasive species in a geographically diverse area that encompasses *m* territorial subdivisions. The surveillance objective is to allocate a fixed amount of resources (such as personnel and budget funding) among the *m* geographical subdivisions in a way that maximizes the potential to determine the pest's extent in the study area, while also meeting the desired level of geographical diversification as a hedge against potential survey failures (such as misplaced surveys or missed detections) which could be caused by errors in estimating the rate or pattern of the species' spread (i.e., uncertainty in the spread estimates). The estimation of the potential monetary benefits from finding new pest incursions can be problematic for a recently discovered invasive organism, since a key component of this calculation – the organism's anticipated economic impact (such as host losses or mitigation costs) – is generally not well characterized. Therefore, we used a non-monetary metric that describes the estimated potential to find the species of concern in a specific geographical region. We treated the performance metric as analogous to the net returns on investment in financial asset valuation. In the latter context, a decision-maker usually strives for higher return values. With respect to pest surveillance, this translates to the acquisition of more information (i.e., as much as possible) about a species' presence.[7]

1.2. Diversification in Pest Surveillance

In financial asset allocation, diversification is considered a useful method to reduce the variance (a measure of financial volatility) of the estimated net returns from an investment portfolio. Typically, a portfolio with higher variance is considered riskier because the likelihood of extreme losses is higher. Portfolios with a relatively large number of asset types may yield lower degrees of financial risk (Luenberger, 1998). The variance of a portfolio can be further decreased when the correlation between the asset types in the portfolio is low or negative (Elton et al., 2010).

In financial asset valuation, risk factors that typically increase the correlation between asset types are generally associated with systematic events that affect all assets in a portfolio, such as general market trends (Elton et al., 2010). However, increasing the proportion of asset types with low or negative correlations improves the stability and reduces the variance of the portfolio given the impacts of these systematic events (Elton et al., 2010). Basically, because asset types with similar (i.e., correlated) behavior fluctuate in value in a similar fashion, a risk-averse decision-maker would find it beneficial to invest in other zero or negatively correlated assets, so that the portfolio's overall value has a lower probability of achieving extreme levels. Increasing diversification also improves the stability of the portfolio in the presence of uncertainty caused by non-systematic events, such as data errors that may distort estimates of the portfolio variance. In our case, diversification of pest surveys is expected to reduce the effects of errors in model-based estimates of the spread of an invasive organism (errors which eventually propagate into the estimates of the expected performance of the survey) and decrease the chance of erroneous selection of survey sites due to incorrect predictions of the pest's pattern of invasion. Errors in allocating surveillance resources are often costly and subsequently imply a penalty. This penalty arises from the trade-off between the desired level of survey performance and tolerated level of uncertainty.

Diversification is also consistent with common decision-making practices for managing outbreaks of invasive pests, where skepticism regarding the accuracy of model-based predictions of spread has caused managers to rely on subjective rules of thumb and allocate surveys in geographical patterns which are more spatially uniform than the model-based spread estimates.

2. Material and Methods

2.1. A Portfolio-based Model of Geographical Pest Surveillance

Consider a surveillance program for a new invasive pest that covers *m* geographical regions. A defined amount of resources is available for the entire program which must be allocated across the *m* regions. Each individual region, $j = 1,\ldots, m$, contains a number of potential surveillance locations, where each location, *y*, is characterized by an estimate, ξ, that depicts the likely outcome if the survey were to be implemented at that location. The distributions of potential survey outcomes (ξ) for the survey regions are estimated prior to survey planning with a geographical model of pest invasion that predicts, in probabilistic terms, the expansion of the invasive pest population over the survey period. (Their descriptions will be presented in Sections 2.4, "Model-based Assessment of EAB Spread With Campers", and 2.5, "Expected Survey Outcome Metric.").

For each region *j*, we constructed the cumulative distribution of the expected survey outcomes from the location-specific ξ values generated with the invasion model. We then sampled these cumulative distributions at 20 successively increasing percentile points spaced at equal intervals between 0 and 1, so each survey region was characterized by a set, $\boldsymbol{I}_j$, of the distribution values I_j at the sampled percentile points. Since the sampling points were identical for all regions, the size, *N*, of set $\boldsymbol{I}_j$ was the same for all regions, making it possible to directly compare sets $\boldsymbol{I}_j$ and $\boldsymbol{I}_i$ for any two regions *j* and *i*.

A survey of *m* geographical regions is conceptually similar to a portfolio of *m* assets in financial analysis; essentially, the proportion, ω_j, of the total surveillance resource allocated to a particular region *j* can be considered analogous to the fraction of investment in a financial portfolio that is allocated to a given asset type *j*. For each of our geographical regions, we treated the set I_j values in the same manner that

[7] Many applications of portfolio analysis to non-financial problems, such as assessments of extreme events (Santos and Haimes, 2004), veterinary management programs (Galligan and Marsh, 1988), resource allocations for flood protection (Aerts et al., 2008; Zhou et al., 2012) or control of multiple exotic diseases in animal health (Prattley et al., 2007), used non-monetary performance metrics (such as exceedance probabilities or disturbance return intervals; see McInnes et al. (2009) and Zhou et al. (2012)), hence our choice of a non-monetary metric felt justified.