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Perspective

Optimal invasive species surveillance in the real world: practical advances from research

Frank H. Koch[1], Denys Yemshanov[2], Robert G. Haight[3], Chris J.K. MacQuarrie[2], Ning Liu[2], Robert Venette[3] and Krista Ryall[2]

[1]USDA Forest Service, Southern Research Station, Eastern Forest Environmental Threat Assessment Center, Research Triangle Park, NC, U.S.A; [2]Natural Resources Canada, Canadian Forest Service, Great Lakes Forestry Centre, Sault Ste. Marie, ON, Canada; [3]USDA Forest Service, Northern Research Station, St. Paul, MN, U.S.A

Correspondence: Denys Yemshanov (denys.yemshanov@canada.ca)

When alien species make incursions into novel environments, early detection through surveillance is critical to minimizing their impacts and preserving the possibility of timely eradication. However, incipient populations can be difficult to detect, and usually, there are limited resources for surveillance or other response activities. Modern optimization techniques enable surveillance planning that accounts for the biology and expected behavior of an invasive species while exploring multiple scenarios to identify the most cost-effective options. Nevertheless, most optimization models omit some real-world limitations faced by practitioners during multi-day surveillance campaigns, such as daily working time constraints, the time and cost to access survey sites and personnel work schedules. Consequently, surveillance managers must rely on their own judgments to handle these logistical details, and default to their experience during implementation. This is sensible, but their decisions may fail to address all relevant factors and may not be cost-effective. A better planning strategy is to determine optimal routing to survey sites while accounting for common daily logistical constraints. Adding site access and other logistical constraints imposes restrictions on the scope and extent of the surveillance effort, yielding costlier but more realistic expectations of the surveillance outcomes than in a theoretical planning case.

Introduction

Risk-based surveillance is a key element of plant biosecurity. Surveillance activities for invasive alien species that are harmful to plants — primarily insects, plant pathogens and weeds — take place in border (or possibly pre-border) and post-border contexts [1,2]. The objective of border surveillance is to intercept these invaders at the introduction or transport stage [3], before they can become established in novel environments [4,5]. Ordinarily, surveillance effort is targeted at or near ports of entry [2], as international trade and travel account for a large share of global species movements [2,6–9]. The detection methods (e.g. trapping or container inspections) and degree of effort applied in these locations is determined through the pest risk analysis (PRA) process, which identifies high-risk organisms as well as the commodity and geographic pathways by which they are most likely transported [2,9,10]. As with all biosecurity activities, adopting a risk basis for border surveillance decisions is critical due to the huge number of potential species introductions and limited resources to perform surveillance [3,6,7,9,11–13].

Because of the high volume of introductions and the inevitability of detection failures, even under the best of circumstances, some pests will make it across the border and establish populations [14]. This necessitates post-border surveillance, which is the focus of this review. Post-border surveillance centers on the idea of early detection [15–19]. The fundamental goal of early detection is to find invasive species populations before they are too large to eradicate [3,4,10,16,20–25]. Besides increasing the likelihood of eradication success, early detection can help to minimize further spread and limit the

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costs of response measures, such as deployment of biological control [5,8,17,21,23,25–27]. There are some practical differences between the three main types of post-border surveillance: detection surveys, which are focused on discovering an invader as soon as possible so that survey attention can be shifted to other locations under threat [14,19]; delimiting surveys, which are intended to find the full extent of a pest population in an invaded area to facilitate response planning [1,28–31]; and 'proof of freedom' surveys to substantiate that a pest is not present in an area of concern [1,32]. However, the three types are conceptually similar in that they prioritize rapid discovery (or instead, rapid confirmation of absence) as a means to lessen the impact of an invasive species [28]. Arguably, the main difference between these types of surveys is the scale of the required sampling effort.

Regardless, a well-devised, risk-based strategy is crucial for post-border surveillance aimed at reliable and timely detection. Risk-based strategies account for variability between potentially invaded locations in terms of a number of relevant criteria, including environmental suitability (e.g. climatic conditions), host availability and the predicted geographic distribution of the invading species [3,29,30,33,34]; more sophisticated strategies account for aspects such as a species' expected pattern of spread, including through spatial networks [35–37], or the consequences of imperfect detection tools [38,39]. Typically, knowledge about these risk criteria is uncertain, especially for newly recorded and therefore poorly understood invasive species [28–30,40]. Nevertheless, there are usually enough data (i.e. spatial data) describing the criteria to design surveys that are far more efficient than schemes that rely heavily on uniform or random sampling [30,33,41].

Although a risk-based approach confers efficiency by narrowing the survey sampling frame, there is the separate issue of cost, which dictates what is feasible when developing a surveillance system [42]. An ideal system ensures reliable discovery of an invader soon after its arrival in an area of interest. Unfortunately, incipient populations are notoriously difficult to find [43,44]. As a practical matter, no detection methods are perfect, and more effective detection methods are usually more expensive to implement [38,39,45,46]. Even when detection is highly reliable, it is inefficient to survey everywhere across all areas at risk with the same degree of effort, since invasions rarely progress across a landscape in uniform fashion [39,41]. Moreover, surveillance is merely one element of post-border response to invasions; regularly, decision-makers must assess the trade-offs of devoting limited resources to surveillance instead of other management efforts [47–50].

Consequently, optimization-based surveillance planning has emerged as a sub-discipline of invasive species post-border response. Modern optimization techniques facilitate surveillance planning that accounts for the biology and behavior of an invader while comparing multiple scenarios to identify the most cost-effective options. Indeed, improvements in computational methods and resources have made it possible to find optimal solutions using complex models with varied formulations and objectives. In the next section of this review, we outline some recent advances in the application of optimization models for post-border surveillance planning. In subsequent sections, we consider the extent to which current optimization approaches capture the many real-world limitations faced by survey managers in the field. We also describe an example of optimization for a multi-day surveillance campaign that incorporates an array of practical constraints.

Optimization approaches to surveillance design

Contemporary work on developing surveillance strategies for invasive species has focused on determining optimal levels of survey effort, sometimes in combination with eradication or other control activities [11,21,44,47,49,51,52]. Other work has explored optimal survey selection in spatial settings [23,50,53,54] and together in both spatial and temporal domains [17,22,45,46,55–57]. In these studies, the survey manager's main objective may have been to minimize the total expected costs associated with an invader (i.e. the economic value of anticipated host losses plus control and mitigation costs) [17,22,53], the expected number of new infestations [23] or the time to first detection of an incipient population [57]. Instead, the objective may have been to minimize the number of invaded or potentially invaded host plants [50] or maximize the number of uninvaded hosts [55]. Alternately, the goal may have been to maximize the expected number of detections [45] or minimize the number of survey sites with false negatives (i.e. where surveys failed to find an established population) [46,56]. Routinely, the survey planning problems in these studies had budgetary constraints on surveillance and other elements of the management response. Further research examples have adapted portfolio theory — an approach from the finance field that maximizes the return on funds distributed among a diverse set of investment assets [58] — to address a somewhat different optimization objective: to allocate surveillance resources for the earliest possible detection, while also hedging against a highly unlikely but catastrophic outcome, i.e. failure to detect a high-impact invader before it becomes well-established and widespread [15,40,50,59].

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A sizeable amount of work on optimal invasive species surveillance has come from operations research literature (see [43] for a review). Optimization models are suited to the complexity of invasive species problems because they take account of the biological and behavioral characteristics of an invader while evaluating the costs and benefits of possible management responses [43,60]. Generally, optimization models applied to invasive species combine simulation models, which depict the uncertain invasion process through space and time, with scenario approaches, such that the optimal surveillance is developed with respect to a large number of plausible invasion scenarios, thereby supporting decisions regarding the effective allocation of response resources [23,43,46,50,56,61]. For invasive species, optimal surveillance decisions specify timing, spatial intensity and configuration of surveys [23,50,52,62], and sometimes offer a choice of detection method based on features of potential survey locations (e.g. host density, proximity to known infestations or site accessibility) [46,56,57].

Recently, optimal surveillance models have incorporated statistical quality control methods to account for possible deleterious outcomes of surveillance failures. For example, acceptance sampling [63] is used in manufacturing quality control as a way to inspect large quantities of products quickly despite limited inspection resources. The basic concept is to accept or reject an entire lot (i.e. a group of items) based on findings from a sample of items in the lot; a lot is accepted only if the number of defective items in the sample remains below a defined acceptance threshold. For invasive species surveillance, this threshold can be interpreted as an acceptable level of risk of failing to detect an invader [64]. Previously, the approach was adapted for optimal inspection of live plant imports to prevent invasive species introductions [11], but it has also been applied in the post-border surveillance context. For instance, a recent study [46] utilized acceptance sampling to compare optimal survey schemes for the emerald ash borer (*Agrilus planipennis*), an invasive forest insect in North America, with the objective of minimizing the expected number of infested trees in sites where surveys failed to find signs of infestation. A related study [56] used the approach when evaluating the effectiveness of a management strategy that combined surveillance with optional removal of host trees conditional on detection, thus minimizing the pest's ability to spread to uninvaded sites.

Optimization approaches may also be used to elucidate the factors that most influence the invasion process or may otherwise affect the likelihood of successful detection. For instance, an analysis of the potential spread of the pathogen *Xylella fastidiosa* in France [65] identified the primary drivers of infection and incorporated them into a network simulation model, which provided a basis for comparing the performance of several surveillance strategies. Another study of the citrus disease huanglongbing (caused by *Candidatus* Liberibacter asiaticus) in the United States [66] evaluated the distribution of surveillance resources as an optimization problem. The researchers found that the sensitivity of available detection methods affected the optimal arrangement of survey sites. The latter study is a relevant example of the capacity to address a practical surveillance concern (i.e. detection sensitivity) through optimization.

Incorporating real-world factors into optimal surveillance

Model-based surveillance optimization may require substantial computing effort, particularly since it almost always involves a spatial dimension [43]. Various mathematical modeling and programming methods (e.g. mixed-integer programming [23,50,60]), facilitated by increasingly efficient optimization software, have made it possible to compute optimal solutions in a reasonable amount of time, usually a matter of hours [43]. This is true even though many optimization studies involving invasive species surveillance have added complexity by incorporating uncertainty in one or more parameters, such as dispersal [23,50,55,57,60], the probability of detection [67] or the current invasion extent [49].

As this suggests, previous research efforts have differed in terms of their sophistication and level of detail, particularly with respect to practical aspects of invasive species surveillance [30]. Some analyses have included considerations like search times at survey sites [21] or travel costs as they relate to the optimal number of site visits [45]. Other research has examined the optimality of varying surveillance effort through time rather than assuming it remains constant [22], or optimal surveillance design when surveys stop (and management efforts begin) after an invader is detected [14].

Most of these examples have addressed one or two practical constraints on surveillance planning. Relatively few studies have attempted to develop broad-scale, multi-day surveillance campaigns (although see [25,37,51]), most likely because their logistical complexity represents a significant modeling obstacle. Multi-day surveillance planning must account for numerous real-world concerns, which include securing access to a variety of sites across the area of interest, allocating visit times to ensure the sites are surveyed adequately and factoring in

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travel times between them — all while remaining mindful of the larger campaign schedule. Furthermore, these logistical details must be managed with regard for daily working time constraints and personnel availability.

In multi-day surveillance planning, many of the key logistical considerations depend on the configuration of the transportation network that enables access to potential survey sites in the area of interest. In geographic transportation networks, such as urban and suburban road networks, optimal planning of survey visits can be achieved with route optimization approaches. Examples of optimal routing problems include the multiple tour maximum collection problem [68], the optimal dispatch problem [69–72], the travelling salesman problem [73], and the prize-collecting Steiner tree problem [74]. A promising approach to incorporate site access and other practical considerations into optimal surveillance planning is to adapt the team orienteering problem [75]. The team orienteering problem attempts to find the shortest possible (or least expensive) path between a set of selected sites, with the constraint that not all sites can be visited within the available time [75,76]. Another constraint is that the start and end points of the path are known and consistent day-to-day (e.g. the headquarters for a survey crew). Further practical constraints can also be integrated into the problem formulation, as illustrated below.

Incorporating real-world factors into optimal surveillance: a conceptual example

For each day in a multi-day invasive species surveillance problem, a survey objective can be formulated as finding a route that visits a sequence of sites with a corresponding set of sampling plans. During the working day, a survey crew visits several sites in the area of interest to conduct sampling (e.g. collecting host plant materials, performing visual inspections or checking traps). These visits are scheduled to fall along a route that starts at the main facility where fleet vehicles are stored and the collected samples (if any) are processed. After the sites are visited, the survey crew returns to the main facility by the end of the day. A surveillance campaign over T days will require planning T routes with accompanying prescriptions of visited sites and sampling rates. The total time that can be spent on survey activities on any day is limited by the working day length (e.g. 7.5 h), which must include time to access the sites, perform sampling and return to the main facility.

To implement the optimal routing model in a spatial setting, an area of N sites (i.e. potential survey locations) must be depicted as a network of interconnected nodes. The nodes depicting adjacent sites are connected by arcs. The optimal scheduling of daily surveys can then be characterized as a problem of finding daily routes through this network of interconnected sites, subject to the working day length constraint and the rule that each route must start and end at the main facility (Figure 1). For a multi-day surveillance campaign of length T, the team orienteering problem determines T routes that maximize the total detection rate at the sites visited along the scheduled routes.

Although not shown here, the optimal routing problem can be linked with the acceptance sampling problem (as implemented in [46]). This would address the vexing issue of failed detections in operational invasive species surveillance. The prospect of failing to detect the presence of an invader when surveying a site is especially high in multi-day surveys, when planners must deal with daily scheduling and the associated complications.

Are real-world concerns the responsibility of the researcher or survey manager?

In our view, accounting for logistical and operational constraints during optimization is crucial to planning productive multi-day surveillance. Adding these constraints to an optimization-based model will restrict the scope and extent of the cost-effective surveillance actions, and so will produce prescriptions that appear less effective than theoretical model solutions that do not account for the constraints. However, these prescriptions will offer more realistic expectations of the surveillance outcomes, which ultimately helps to protect the credibility of the surveillance plan as well as the integrity of the results.

In the absence of guidance from researchers, survey managers must rely on their own judgments and experience when implementing the surveys. This is a sensible approach, but the complexity of the multi-day surveillance problem can cause managers to overlook relevant details, such that the campaign is not truly cost-effective. There is also some risk that adjustments made in the field alter the campaign in some meaningful way, but those changes are not reported to the researcher who performed the optimization; in turn, the researcher cannot evaluate their impacts on the optimal prescriptions. We recognize that some day-to-day

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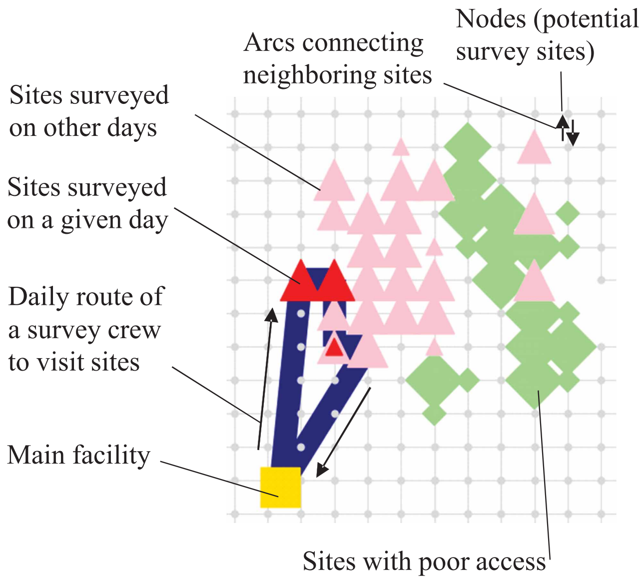

Figure 1. Conceptual example of optimal routing for a multi-day surveillance campaign.
The area of interest is represented by a network of nodes (potential survey sites) interconnected by arcs. Each day, the survey crew leaves the main facility and follows a route that takes them to a set of survey sites before returning to the facility at the end of the day. Daily route scheduling must account for several practical factors, including site visit times and travel times between them, as well as any site access limitations. All activities must take place within the specified working day length.

considerations (e.g. the effects of weather on site visit times and travel times) are difficult, if not impossible, to integrate into optimization models. Nevertheless, we contend that relieving some of the decision-making pressure on a survey manager increases the chance of a successful campaign.

Furthermore, incorporating realistic constraints and features into optimal surveillance models is a logical extension of prior research. It also honors the fundamental aim of post-border invasive species surveillance: reliable early detection. In short, a higher degree of realism enables the development of a stronger decision support system where survey managers are not forced into adjusting model-derived (and presumably optimal) prescriptions based on their local knowledge. Instead, by giving the managers real-world choices, it should be possible to curtail these on-the-fly alterations and interpretations of the prescriptions, and through that improve the robustness of surveillance campaigns.

Summary

- Early detection of invasive alien species through surveillance is essential to limiting their impacts.
- Optimization-based surveillance planning accounts for the characteristics of an invasive species while exploring multiple scenarios to identify prescriptions that make the best use of limited resources.
- Most optimization models omit some of the real-world limitations faced by managers during surveillance campaigns, forcing the managers to handle these concerns themselves.
- New optimization approaches utilize concepts such as optimal routing to incorporate these types of logistical constraints into the surveillance planning process.

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Competing Interests

The authors declare that there are no competing interests associated with the manuscript.

Author Contribution

F.H.K., D.Y. and R.G.H. conceived of the ideas for this manuscript. F.H.K. wrote the first draft and coordinated the revisions. All authors contributed to writing and editing.

Abbreviations

PRA, Pest risk analysis; USDA, US Department of Agriculture.

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