FRQNT B3X Application Package

Title (in French)

La prise de décisions optimales pour le gestion et surveillance des espèces invasives de ravageurs forestiers

Title

Optimal decision making for invasive forest pest management and surveillance

Abstract (500 words)

Abstract (500 Words, in French)

PhD Title

Predicting Forest Pests: Generalized models for predicting spread, economic impacts, and management decisions

PhD thesis summary (300 words)

The primary goal of this thesis is to identify largescale generalities across species invasions. Arguably, due to the dominant role of humans in species invasions, many of the drivers of invasive species establishment, spread, and associated economic damages should be common among invading species. However, whether generalized predictive models are possible or whether species must be modelled and fit separately to account for idiosyncrasies remains unanswered. In Chapter 1, I built a single, general model for the spread of all invasive forest pests in the United States that explained more than 75% of the variation in all pest distributions. In Chapter 2, I contrasted this general model with more complex single-species models, and generated semi-generalized models using simple species-specific correction factors. I found that single-species models underperformed compared to semi-generalized models that incorporated cross-species generalities. In Chapter 3, I synthesized my forecasts of future pest invasions with models of urban tree distributions, tree mortality, and management responses to project future spatiotemporal economic damages to urban trees. I found that future annualized damages could be as high as $170M USD and could result in up to 13 million street tree deaths by 2050. In Chapter 4, I am building a general invasive forest pest establishment model to explore the effect of host diversity on forest pest establishment. When host diversity is measured as total evolutionary history, I find it to be positively related to pest invasion success, which I hypothesize is due to a sampling effect, but when host diversity is measured as dissimilarity to a focal host, I hypothesize that its relationship will be negative due to the linkage between shared evolutionary history and invasibility. These analyses produce general, largescale predictions across invasion stages that act as useful inputs in creating invasive species control programs to limit associated economic damages.

PhD status

I plan to submit this thesis by Spring- early Summer 2020. Chapters 1 and 2 are published in Ecology Letters and Ecological Applications, respectively, while Chapter 3 requires a few final analyses and both Chapters 3 and 4 require editing of their respective manuscripts. I am scheduled to present my PhD thesis seminar – my final degree requirement prior to thesis submission, in the Winter 2020 semester.

PhD Linkage with postdoc (300 words)

My postdoc research will flow directly from the results of my PhD thesis as a more applied extension of my earlier research that follows many of the same themes. The postdoc project complements the search for generality in invasive species spread, establishment, and subsequent damage with a search for generality in optimal invasive species management and surveillance. Over the course of my PhD, I focused on descriptive models of invasions across species at large scales, including models of dispersal and persistence, as well as descriptive analyses of future pest damages, without exploring the role of alternative management scenarios. I intend to move from a descriptive to a prescriptive perspective in my postdoc, and use model projections of pest distributions according to future treatment and quarantine scenarios to determine optimal management strategies. My existing models of pest distributions, host tree distributions, and subsequent host tree mortality will be used directly as inputs to the optimization schemes created. The economic analyses from my thesis Chapter 4 can then be updated according to different future management scenarios to determine how quarantines and treatment regimens would impact future pest dispersal and subsequent tree mortality and economic loss. Additionally, value of information analyses would incorporate uncertainties uncovered in the pest distributional models from my PhD in order to determine the relative benefit of increasing surveillance to more accurately delineate pest distributions, versus allocating budgets toward active quarantine and treatment. These analyses will help determine whether humans are not only allowing for invasion risk to become more predictable, but also creating situations where the optimal treatment, quarantine and/or surveillance actions are also consistent across forest pest species, space, and time.

Project Description (2 pages) Décrivez clairement votre projet de recherche en précisant, dans l'ordre: a) la problématique, b) l'approche théorique, c) les objectifs, d) la méthodologie ou la démarche utilisée (évitez les abréviations).

1. **Research question**

This postdoc will seek to create general, multispecies frameworks that optimize the management and surveillance of forest pest invasions across space and time. Invasive forest pests cause billions of dollars of damages within North America alone, and to limit their damages across space, forest pest managers are tasked with limiting their rates of successful dispersal. Quebec has been the target of several highly damaging invasive forest pests and pathogens, with Dutch elm disease (*Ophiostoma ulmi*) killing nearly all elm trees in the province in the 1950s, and Gypsy Moth (*Lymantria dispar*) infesting large swaths of deciduous forest throughout the last century. Most recently, the emerald ash borer (*Agrilus planipennis)* has decimated the urban ash population.

Urban trees tend to be the main target of economic damages due to invasive forest pests, where their infestation reduces property values and requires municipal governments and property owners to invest heavily in treatment and control regimens [1]. The Ontario Centre on Spending estimates the annual cost of invasive species to an average municipality at $381,000. Within Quebec, vast numbers of infested trees are being treated and cut in major cities such as Montreal and Quebec city. For species such as Emerald Ash Borer that have reached high population levels, eradication is highly unlikely, but if future risks of new invaders to the region were well understood, rapid responses could limit or even prevent new establishments of pest species. Such early eradication programs are proving successful against Asian Longhorned Beetle (*Anoplophora glabripennis*) infestations in Toronto.

Given limited managerial budgets, decisions must be made about the best use of funds in order to limit economic losses and/or maximize the number of healthy trees. Decision theoretical tools are commonly used in concert with species distributional estimates to optimize spatiotemporal resources in a variety of conservation planning problems, including the surveillance and eradication of invasive species [2]. The gypsy moth (*Lymantria dispar*) Slow the Spread campaign within the United States is an example of the use of decision theory for invasive pest control, and is estimated to have reduced gypsy moth spread rates by 70%. While success stories exist, there are substantial risks to poor management decisions in combatting forest pest invasions. This has been the case in Canada, where inadequate delineation of emerald ash borer quarantines has left ash species critically endangered.

While few other coordinated efforts exist for invasive forest pest control in North America, largescale management is likely feasible for more of these pests, and is an area where generalities may emerge across space, time and species. I have provided evidence through previous work for a theory that humans are increasing the largescale predictability of forest pest invasions due to their long-distance transport mechanisms, and hypothesize that these same mechanisms lead to broadscale predictability in the ideal pest management strategies.

Existing decision theoretic approaches have typically relied on spatial simplifications of underlying invasion processes such as establishment and spread [3]. However, anthropogenic dispersal mechanisms require models with a high degree of spatial complexity, which may produce highly divergent optima to previous methodology. For instance, conventional control strategies assume that it is optimal to target the leading edge of a pest invasion to limit future spread [4], without regard for spatial attractors of pests, such as the ability of major cities to act as hubs of long-distance transport.

Another major challenge to designing effective management schemes is that any monitoring data on pest distributions are necessarily presence-only, meaning that the true distribution of a pest is uncertain, since its establishment operates beneath detection records. Increased budgetary allocation towards surveillance programs would allow for increased certainty in pest distributions, but budgets are limited, and it is often unclear clear whether money would be better spent on surveillance or active management protocols. Value of information theory (VOI) allows researchers to explicitly model the benefit of monitoring to resolve uncertainties, and has recently been expanded to cases of multiple spatial units managed simultaneously. Questions of when to monitor and when to act across space have been examined in the reverse case for threatened species [5], but the analogous question of when to focus on detecting and delineating invasive species distributions versus when to invest on active treatment and quarantine protocols remains unanswered.

I would like to explore two main hypotheses with this work: 1) There are generalities in optimal management across species, both in the best spatiotemporal strategies for active management, and in the budgetary balance between active management and improving pest distributional knowledge through surveillance regimes, and 2) Accounting for differential spread across space alters decisions for spread management compared to conventional approaches.

1. **Theoretical approach**

The calculation of associated costs and benefits to different management and surveillance scenarios requires the fitting and calibration of a variety of sub-models for underlying invasion processes and associated economic losses. I produced several such models over the course of my PhD research, but will be expanding on them to more effectively model both directional invasive spread and cyclical dynamics of outbreaking pest species. I previously created estimates of future street tree losses in the absence of management based on a combination of pest dispersal models, street tree distributional models, host tree mortality models, and models of human behaviour in response to tree mortality. I produced these models for all major economically-damaging United States invasive forest pests – many of which are also highly damaging within Canada, and extrapolated model results to approximately 30,000 United States communities. Given alternative management strategies, the ability of pests to spread between sites will be altered, since quarantine measures can be used to limit dispersal into and out of sites. Largescale treatment and spraying protocols can also be used to limit pest densities within different sites. These treatment and quarantine decisions will be used to update models of pest dispersal, which will subsequently flow through to divergent patterns of future host tree mortality and economic loss.

The previous models of forest pest distributions all possess some degree of uncertainty, which could feasibly be ameliorated with increased budgetary spending on surveillance efforts. The influence of this uncertainty can be examined with VOI analyses, where management outcomes can be compared across a variety of levels of model uncertainty to determine the ideal balance between money spent on surveillance and money gained from improved management decisions.

I will compare optimizations of ideal management scenarios with heuristic or rule-of-thumb approaches to determine whether simpler methods of allocating management resources can approximate optimal outcomes.

1. **Goals**

I will use these approaches to determine whether there is a generally optimal pest management strategy across species, space and time, both in terms of where to act using active management and how much of a managerial budget to allocate to monitoring versus surveillance. If there is not a globally optimal strategy for management across species, I will determine whether species traits are correlated to ideal management styles (for instance, if there is a general rule-of-thumb applicable to wood boring species and another more useful in managing defoliating species). I will also provide all data and code necessary to apply these approaches on an open access platform to make optimizations easily accessible to managers to implement within their own contexts. I will also disseminate information on the rules-of-thumb uncovered if they are found to provide useful approximations of optimal management behaviour.

1. **Methodology**

Pest distributional and tree distributional models will be built in the R environment. The existing spread model will be expanded to account for new advances by Canadian researchers (James, others?) in characterizing outbreaking pest population dynamics for species such as Gypsy Moth that display cyclical behaviour. The pest spread model operates as a spatially explicit simulation where the probability of dispersal between grid cells and the pest population density within each grid cell can be modified to simulate different management actions. Quarantines will be modelled as setting the probability of dispersal to zero, while spraying and treatment will be modelled as reducing the pest population density within each cell. Forest tree information for the United States is available from the Forest Inventory and Analysis Program, and estimates of future forest losses can be calculated from existing tree volume data. The street tree models are fit using zero-inflated approach, using a combination of generalized additive models and boosted regression trees. Other types of urban trees (e.g. park and residential trees) can be similarly modelled to extend economic analyses beyond street trees. These models are synthesized with a Bayesian framework that I created and implemented using the R version of the STAN Bayesian modelling language (*rstan*) to predict long-term tree mortality following pest exposure that synthesizes broad databases of empirical tree mortality data to produce the best estimate for a given pest-host combination. The combination of these submodels is then joined to a simple model of the human response to tree mortality that assesses economic loss in terms of tree removal and/or replacement costs.

A major challenge with the optimization of multiple spatiotemporal planning units is that the problem scales to 2n,where n is the number of planning units, thereby necessitating the use of advanced computational tools formulated for high levels of dimensionality. Optimizations will be performed using the GUROBI optimization software implemented with the Python *gurobipy* library. The pest dispersal model will be reformulated as a mixed-integer linear program (MILP) that will use the previously modelled pest and tree distributional estimates and tree mortality estimates to determine the series of cells to manage and the management action to perform in each cell that optimizes some objective function under a fixed budget. The problem will be explored both as a maximization of surviving host trees and as a minimization of future economic losses under a constant budget. Contrary to past optimizations that have been applied to invasive species management [3], this approach can account for interactivity in pest management responses across timesteps, where the effect of management at each site depends on which other sites are managed across time. For instance, while core invasion sites may appear optimal to treat when examining immediate benefits, these sites may be the most readily re-invaded at future timesteps.

To determine the relative effectiveness of conventional management strategies, the objective function will be calculated for typical management scenarios, and compared to the optimum derived from GUROBI. In order to define rules of thumb, optimizations will be examined for common spatiotemporal patterning, and the objective function will be calculated based on simple heuristics derived from these common patterns, and similarly compared to the optimal value. Open-source software will be made available based on the analyses so that managers can assess the priority sites and recommended budgetary allocation between surveillance and active management for pests within their respective region. Rules-of-thumb approaches will also be visible on this tool.

Bibliography (3-5 references)

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Impacts (Démontrez l'importance du projet de recherche, précisez sa contribution au développement des connaissances et justifiez le choix du milieu de recherche. ) 1 page

continued collaboration with US forest service – making use of more widespread forest inventories and urban tree data, cities like montreal also producing urban tree inventories, can forecast damages

Beyond urban tree losses, a similar approach could optimize management to limit forest timber losses or property value losses based on extensions of existing economic models.

In addition to the set of United States invaders that have already established, this approach can be used to pre-meditate the best management response to future pest species based on their likely initial introduction locations. Given the flexible, modular structure of this approach, the analysis could be extended to agricultural pests based on analogous models of their host crop distributions. In Quebec, a species of particular concern to agribulture is the Brown Marmorated Stink Bug, who has recently been discovered in Montreal and could pose a major threat to crops if it spreads beyond urban areas.

My existing models are built for United States forest pests, but an analogous approach would be possible for pests of specific interest to Quebec, such as emerald ash borer, brown marmorated stink bug, and Japanese beetle, and to examine associated urban tree damage to Quebec communities from these pests.

Mountain pine beetle moving east? HWA with climate change, many species central to the model important future threats for quebec

It is of fundamental interest in ecology to determine whether general rules govern invasions sufficiently to make predictions across species using common models and frameworks. Such general rules also have considerable applied value in allowing potential new pest threats to be predicted and management to be planned before they have even established within a region.

Predictive models of each phase of invasion, coupled with scenarios of economic loss given alternative management actions, will allow managers to take the most effective pest control actions. Thus far, this project has largely been applied to United States pest data due to my collaboration with the U.S. Forest Service. However, all of these models can easily be adjusted to accommodate Canadian invasive species data. While these models were originally fit to United States data, they are highly relevant to Quebec and Canada at large, as many of the same invasive forest pests infest these areas. One major future threat to Quebec that is already causing damage within Canada is Mountain Pine Beetle (latin) – a pest native to Western Canada that is beginning to invade outside of its historical range. An important feature in the dynamics of Mountain Pine Beetle is its outbreaking behaviour, where cyclical population dynamics emerge across time. My existing models do not capture cyclical outbreak dynamics, but its incorporation could improve model predictions for other invasive forest pests such as Gypsy Moth that also display such dynamics. I will be partnering with researchers across Quebec and Canada at large (Patrick James, others?) to incorporate a cyclical population dynamical component into my existing spread models.Alternative dispersal models can easily be substituted to move from terrestrial to aquatic transport in order to predict the spread of aquatic invaders that may threaten Quebec’s fisheries such as the Eurasian Water Milfoil (latin). The development of these tools will increase the ability of Canadian pest managers to accurately forecast future species invasions and reduce their impacts, thereby strengthening crucial components of Canada’s economy such as the forestry and fisheries sectors.

This model would have immediate value to forest managers, as it could be used to determine the most effective allocation of government funding for invasive species management. If generality in optimal management is observed, this model could produce useful heuristics for the best management practices across all invasive forest pests. This would allow for time savings in the development of management plans, since precise optima would not need to be calculated, and far less data would need to be collected prior to taking action, thereby allowing for rapid responses to invasion threats.

These analyses will help determine whether humans are not only allowing for invasion risk to become more predictable, but also creating situations where the optimal management or surveillance actions are also consistent across forest pest species, space, and time. This search for generalities allows for more effective future planning, since invasions can be predicted *a priori* even in situations of limited data, and may allow for increased ease-of-use and potential uptake by managers when designing management plans, since it allows for the generation of heuristic tools for optimal budgetary allocation and rules of thumb for optimal quarantine or treatment sites.

Partnerships with Patrick and rest of team – synthesize with models of outbreak population dynamics/more spatial than temporal- increases realism of models for species with outbreak dynamics such as gypsy moth – more cyclical damage patterns, may require different management schemes, also MPB which is outbreaking but also acting more like invader as it moves eastward

Flexible, modular structure allows for applicability across geographies and systems (forest, agriculture, urban, even aquatic)

Justification of host environment - **[Justification du milieu d’accueil](https://frqnet.frq.gouv.qc.ca/researchPortal/faces/forms/index.xhtml)** - Justifiez le choix de votre milieu de recherche en termes de qualité et de pertinence. 1 page

When to monitor and when to act – recently explored in the opposite context for preserving threatened species and budgetary considerations of either monitoring or managing

Carleton – 34 adjunct faculty in biology with govt organizations, national wildlife research centre, agriculture and agrifood, Canadian museum of nature, great lakes fishery commission, DFO

Outside Quebec???

Collaborations with uq

Existing projects involve Using value of information techniques to help decide when we should gather more information and when it makes sense to act on the information we have, Developing tools to optimize conservation of places, threats, or species, Predicting the trajectories of species invasions, and optimizing management to prevent invasive species impacts

Carleton is a mid-tier university with a steadily increasing reputation, many highly productive young researchers. Within the field of conservation, many leaders, including Lenore fahrig, steve cooke.

The national wildlife research centre is onsite, and partnerships across campuses are very common, links very strong, interaction with national-level research scientists, many professor collaborations, committee membership is shared, students study across campuses, Ottawa is home to a large number of national-level government agencies, NRCan, AgCan, large number of adjunct professors who are researchers at these organizations.

Joe – early career highly productive, 6 postdocs, many new publications, existing partnerships with many government agencies,

Prof. Bennett’s large group of postdoctoral researchers would be a very stimulating research setting. While researchers study similar themes to my current lab, namely invasive species modelling and decision theory, it would be highly beneficial for me to approach these themes from the collaborative, interdisciplinary perspective present. The sheer size of the group means that their research is inherently collaborative, and the interdisciplinary nature of lab members greatly increases the strategies employed to solve problems.

Fit between the research environment and the career plan – diverse experience on more applied questions, economics synthesized with ecology, more multidisciplinary lens, big data, largescale conservation problems

Fit w supervisor’s field, quality and recognition – early stage but rapid progress and already a great deal of recognition – fosters a healthy, equitable work environment for a diversity of researchers

Mentionnez tout ce qui peut démontrer votre implication sociale, votre leadership et vos habiletés de communication. (1 page)

I have given 3 guest lectures, 2 invited seminars, 3 international presentations, 3 regional presentations, and 2 departmental presentations on my research.

I have been responsible in planning and conducting lab and computer-based research at McGill since 2013, but also have four years of field research experience. My PhD project was developed in concert with my graduate supervisor, and have yearly meetings with my supervisory committee (composed of my supervisor and two other professors of ecology) to gauge my progress and the feasibility of my planned research. Across these meetings, I have always shown satisfactory progress. Eight months into my PhD, I had a qualifying exam, where I defended my PhD proposal to an examining committee, who judged me based on my literacy in my particular field of study, the feasibility and novelty of my proposed research, and my research communication skills through oral and written means. I completed this exam successfully, with no changes required to my proposal. Dr. Leung and I have recently completed a side-project in Panama, where we synthesized survey and presence-only records of all plant species to model the distribution of Panama's entire plant community. We collaborated with an undergraduate student and a Panamanian government researcher to make this project a success. The manuscript that resulted from this project is now published in Ecological Applications. The work is far-removed from my PhD work, indicating a breadth of fields in which I can plan and conduct highly acclaimed research. In winter 2018, I planned and executed a 3-month research trip to Australia, to work at the Centre for Excellence in Environmental Decisions with Drs. Hugh Possingham, Eve McDonald-Madden, Iadine Chades, and other researchers. I decided on my project and timeline myself, got in contact with my host organization, obtained funding through a Michael Smith Foreign Study Supplement, found housing, and had a very successful visit. I am in the process of writing the manuscript that emerged from this fruitful collaboration. This project was not directly related to the skills I had learned so far in my PhD, demonstrating my ability to seek out experts in a variety of fields in order to grow my conservation science skillset. On my own time, I decided to collaborate with my sister, who was working at the IUCN Maldives, in order to create and publish models of sea turtle occurrence across the Maldives based on citizen science data. I am passionate about the power of statistical tools in advancing conservation legislation, and am happy to have helped to provide support for a ban on turtle harvesting in the Maldives. We have continued to work with these data, and are currently developing population estimate models. Prior to my Honours work, I worked with three different teams of researchers across a variety of disciplines. In my home province of New Brunswick at UNB's Canadian Rivers Institute hub, I aided graduate students in their various projects for four summers with the help of four USRA grants. My research ranged from hydrological mapping of the river basin, to lake classification, to fish stock and community assessment, to macroinvertebrate sorting. During my third year of undergraduate studies, I worked on an independent research project studying the behaviour of Gammarus pulex, an invasive amphipod species in Ireland, in response to brown trout chemical cues. I worked under the supervision of PhD student Josephine Iacarella in Dr. Anthony Ricciardi’s lab. I collected over 60 hours of behavioural data while coding the amphipod behaviour in JWatcher, and built general linear models in R. Josephine and I published our results in the Canadian Journal of Fisheries and Aquatic Sciences. My earliest work was in Dr. David Green's Lab, at McGill, where I measured American and Fowler’s toads and mined morphological data from online museum databases for PhD student David O’Connor's phylogeography project. These first two projects primed me to become an efficient graduate student capable of managing my time effectively and exposed me to a variety of supervisory styles that I now draw from when interacting with more junior researchers. I currently help to supervise undergraduate students who have help me to collect data, at times employing state-of-the-art web scraping tools to do so.   
 equity work, TAships, securing of funding consistently, msfss, conferences, involvement in student government, seminars, activity on twitter/github, pubs outside of main field, main focus on equity work

QCBS as a Québec strategic research cluster – continued participation