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Exploring critical uncertainties in pathway assessments of human-assisted introductions of alien forest species in Canada

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ABSTRACT

Long-distance introductions of alien species are often driven by socioeconomic factors, such that conventional "biological" invasion models may not be capable of estimating spread fully and reliably. In this study, we demonstrate a new technique for assessing and reconstructing human-mediated pathways of alien forest species entries to major settlements in Canada via commercial road transportation and domestic trade.

We undertook our analysis in three steps. First, we used existing data on movement of commodities associated with bark- and wood-boring forest pests to build a probabilistic model of how the organisms may be moved from one location to another through a transportation network. We then used this model to generate multiple sets of predictions of species arrival rates at every location in the transportation network, and to identify the locations with the highest likelihood of new incursions. Finally, we evaluated the sensitivity of the species arrival rates to uncertainty in key model assumptions by testing the impact of additive and multiplicative errors (by respectively adding a uniform random variate or symmetric variation bounds to the arrival rate values) on the probabilities of pest transmission from one location to another, as well as the impact of the removal of one or more nodes and all connecting links to other nodes from the underlying transportation network.

Overall, the identification of potential pest arrival hotspots is moderately robust to uncertainties in key modeling assumptions. Large urban areas and major border crossings that have the highest predicted species arrival rates have the lowest sensitivities to uncertainty in the pest transmission potential and to random changes in the structure of the transportation network. The roadside survey data appears to be sufficient to delineate major hubs and hotspots where pests are likely to arrive from other locations in the network via commercial truck transport. However, "pass-through" locations with few incoming and outgoing routes can be identified with lower precision. The arrival rates of alien forest pests appear to be highly sensitive to additive errors. Surprisingly, the impact of random changes in the structure of the transportation network was relatively low.

1. Introduction

Large-scale domestic and international trade, involving the relatively rapid and long-distance transport of immense quantities of raw commodities and finished goods, has become a defining feature of the world economy. In North America and elsewhere, the proportional growth of trade volumes is expected to exceed the rate of economic growth (UNCTD, 2007; WTO, 2008). The transportation corridors that facilitate all of this trade have also become critical gateways for introductions of alien species: non-indigenous insects, pathogens, and other organisms are often inadvertently transported

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to novel territories in shipping containers and commercial transports, where they may become established as ecologically and/or economically harmful pests (Hulme et al., 2008; Hulme, 2009; Kaluza et al., 2010; Lounibos, 2002; Westphal et al., 2008).

Increasing levels of trade and complexity of transportation networks have been recognized as key drivers of ecological invasions (Bain et al., 2010; Pysek et al., 2010; Bradley et al., 2012). Recent studies have linked the long-distance spread of alien species populations to anthropogenic transport (Blakeslee et al., 2010), patterns of historical trade and settlement (Brawley et al., 2009), marine trade (Bain et al., 2010; Kaluza et al., 2010) and recent economic and demographic benchmarks (Pysek et al., 2010). Notably, quantitative assessments of how alien organisms may be carried through a transportation network and subsequently introduced at various locations remain limited in scope. In part, this may be attributed to the growing complexity of modern transportation networks as well as a multitude of potential socioeconomic factors that influence local and global trade flows, and thus, the associated movements of alien species (Pysek et al., 2010). Furthermore, the capacity to realistically assess the invasion potential of any individual species is usually constrained by a lack of reliable data about the organism's biology and behaviour, as well as time pressures faced by decision makers when attempting to craft an appropriate response to new (or anticipated) incursions. In this situation, rapid assessments of the potential origins of new (or anticipated) species introductions can serve as an important starting point in identifying possible pest outbreaks and strategizing immediate response and screening measures.

When planning rapid-response activities after the discovery of a new invader, decision makers often need to identify, at least in approximate terms, the potential of the species to invade the location(s) of interest (Lodge et al., 2006; Muirhead et al., 2008). These assessments can be undertaken with modeling tools that trace the movement pathways of an alien organism to locations of interest from its suspected region(s) of origin (e.g., Carey, 1996; Muirhead et al., 2006; Wang and Wang, 2006; Pitt et al., 2009). Since a pest found at a particular destination may have originated from multiple locations, such estimates of species arrival are rarely precise, and often have a considerable degree of uncertainty.

In this paper we present a new analytical technique that helps quantify the potential of an invasive pest to arrive at the location(s) of interest from elsewhere. We employ a pathway model that traces the arrivals at the location(s) of interest back to multiple origin locations, and thus offers an advantage over typical cellular automata spread models. Compared to common forward-looking models that predict spread rates with a distance-dependent dispersal probabilistic kernel, the pathway model does not have the same distance constraint. The predicted arrival rate at a given destination location accounts for the possibility of spread from all potential origins based on the configuration of the spread pathways, regardless of distance. By being comprehensive with respect to origins, the model has better capacity to address the contribution of long-distance, human-mediated dispersal.

We concentrate on predicting human-assisted movements of bark- and wood-boring insects with commercial freight transportation through the road network in Canada and the U.S. Similar research in the past suggested that volumes of transported commodities and freight that may harbour alien organisms can be used to predict the likelihoods of unintentional introductions of non-native organisms across large geographic regions (Drake and Lodge, 2004; Hlasny and Livingston, 2008; Tatem et al., 2006; Westphal et al., 2008; Yemshanov et al., 2012b). We performed our analysis within the setting of a complex network of transportation corridors and used existing data on shipments of commodities and cargoes that have been historically associated with alien forest insects (Table S1.1, Appendix S1) to characterize the network. With respect to the analytical results, we primarily focused on municipalities and major border crossings in Canada, but given the high degree of integration between the U.S. and Canadian economies, we also traced movements of pest-associated commodities from and to the U.S.

In terms of systematic groups, we used the same insect families of bark- and wood-boring forest insects as presented in Koch et al. (2011) and Yemshanov et al. (2012a). This work relates to our previous geographic analysis of alien species' entry potential from major Canadian ports (Yemshanov et al., 2012a), but instead of focusing on aspects of alien species arrivals associated with international trade, our objective was to identify general patterns and critical uncertainties associated with the potential movement of alien forest insects through the domestic (i.e., intra-continental) transportation network in North America and to identify important pathways, "hubs" (cf. Floerl et al., 2009) and "crossroad" locations in the network.

2. Methods

2.1. The pathway analysis concept

Consider a transportation network that describes the likely movements of a non-native organism within a region of interest based on the shipment patterns of particular cargoes or commodities known to harbour the pest. The network consists of a set of n locations, or nodes. We assume that any node in the network could be either an originating location for the pest or a site where the pest might be detected. The nodes in the network are connected by a system of pathways. Each corridor has an associated volume of pest-associated commodities that are transported through it during a certain time period. In the general case, the movement of a pest with commercial transportation can be described by a system of ij vectors, each of them depicting the flow of pest-associated commodities between a pair of network nodes, i and j.

We conducted the analysis in three major steps. First, we used existing data on movement of commodities associated with forest pests (i.e., wood- and bark-boring insects) to build a probabilistic pathway model of how these organisms may be moved through our transportation network. Next, we used the pathway model to generate multiple sets of estimates of the pests' patterns of movement from each individual network node (i.e., one candidate origin location at a time) to elsewhere in the network. The pathway model output is a list of the estimated transmission rate values for all unique "origin–destination" pairs of nodes. We then rearranged this list so each destination location would have an associated distribution of its potential origin locations and associated transmission rate values. From this vector we then estimated the average rate at which a species of interest could be expected to arrive at a given location from the other nodes in the network. We summarized these location-specific arrival rate estimates by ranking major Canadian settlements and U.S.–Canada border crossings by their potential to receive alien forest species with commercial freight shipments from other regions in Canada and the U.S. through the transportation network. As a last step, we tested the sensitivity of the rankings to uncertainty about key pathway model parameters, such as the basic configuration of the transportation network and the probability of pest transmission between network nodes.

2.2. Step 1: developing a probabilistic pathway model of pest movement through the transportation network

2.2.1. Data on movement of pest-associated commodities

For this study, we made the assumption that the probability of human-assisted spread of forest pests with commercial transportation is related to the volume of pest-associated commodities moved