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Modeling urban distributions of host trees for invasive forest insects in the eastern and central USA: A three-step approach using field inventory data

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ABSTRACT

Despite serving as invasion gateways for non-native forest pests, urban forests are less well understood than natural forests. For example, only a fraction of communities in the USA and Canada have completed urban forest inventories, and most have been limited to street trees; sample-based inventories that provide valid community-wide estimates of urban forest composition are much rarer. As a proof of concept, we devised a three-step approach to model urban tree distributions regionally using available street tree and whole-community inventory data. We illustrate the approach for three tree genera – ash (*Fraxinus* spp.), maple (*Acer* spp.), and oak (*Quercus* spp.) – that are hosts for high-profile insect pests. The objective of the first step was to estimate, for communities with only street tree inventories, the proportion of the community's total basal area (BA) in each host genus. Utilizing data from communities with paired street tree and whole-community inventories, we applied polynomial regression to estimate whole-community BA proportion per genus as a function of a community's street tree BA proportion and its geographic location. The objective of the second step was to estimate per-genus BA proportions for communities in our prediction region (eastern and central USA) with no urban forest inventory. We used stochastic gradient boosting to predict these proportions as a function of environmental and other variables. In the third step, we developed a generalized additive model for estimating the total BA of a community as a function of its canopy cover, geographic location, and area. We then combined the outputs from the second and third steps to estimate ash, maple, and oak BA for the nearly 24,000 communities in our prediction region. By merging these estimates with similar information on natural forests, we can provide more complete representations of host distributions for pest risk modeling, spread modeling, and other applications.

1. Introduction

Invasive species have tremendous impacts globally, including disruption of ecosystem functions, loss of important agricultural crops, declines and extinctions of native species, damage to infrastructure, and direct as well as indirect (e.g., as a vector) effects on human health (Parker et al., 1999; Allen and Humble, 2002; Clavero and García-Berthou, 2005; Bradshaw et al., 2016). These impacts are challenging to specify in economic terms. For example, insects, which comprise one of the largest classes of invasive species, recently were estimated to have an annual impact of US$77 billion worldwide in terms of direct losses of goods and services, control costs, and associated human health costs (Bradshaw et al., 2016). However, because there have been few dedicated assessments of the economic impacts of insects, this number likely underestimates the true costs by a large margin (Bradshaw et al., 2016).

Forest pests (i.e., insects and diseases that affect trees) account for a considerable fraction of the impacts of all invasive pests of plants (Liebhold et al., 1995; Kenis et al., 2009; Paini et al., 2016). For instance, more than 450 non-native forest insect species have become established in the continental USA since European settlement (Aukema et al., 2010). Out of these, a subset of 62 high-impact species were estimated to cost nearly US$1.7 billion annually in government expenditures for management and control, and another US$830 million in lost residential property values (Aukema et al., 2011). By changing

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forest composition and structure at a regional scale, forest pests also affect critical ecosystem functions such as nutrient cycling and wildlife habitat (Lovett et al., 2016). In urban forests (i.e., forests in cities, suburbs, and other human settlements), extensive tree loss caused by pests has been linked to negative impacts on human cardiovascular and respiratory health (Donovan et al., 2013).

As with other categories of invaders, most forest pest invasions have occurred as a result of human activities, especially the intentional or accidental movement of species by trade or travel (Mack et al., 2000; Perrings et al., 2002; Hulme, 2009). Urban forests play a principal role in facilitating such invasions (US Government Accountability Office, 2006; Colunga-Garcia et al., 2010b, 2010a; Koch et al., 2011). Many invasive species, including forest pests, are discovered initially in urbanized areas, which are frequent destinations for international cargo and passengers (Colunga-Garcia et al., 2010b; Huang et al., 2012; Liebhold et al., 2013). In the USA, insect species such as the European gypsy moth (*Lymantria dispar dispar* L.; EGM), emerald ash borer (*Agrilus planipennis* Fairmaire; EAB), and Asian longhorned beetle (*Anoplophora glabripennis* (Motschulsky); ALB) first emerged as pests in urban forests (Liebhold et al., 1995; Poland and McCullough, 2006; Dodds and Orwig, 2011). Historically, urban forests have high rates of invasive pest introductions (e.g., insects harbored by live plants for landscaping purposes) and may provide habitat that is more conducive to invasive pest establishment than natural forests, with fewer natural enemies, greater abundance of preferred hosts, and favorably altered environmental conditions, for example due to the urban heat island effect (Alvey, 2006; McKinney, 2006). Furthermore, portions of many urban forests in North America are dominated by a single tree species, and the trees are often planted closely together, facilitating the spread of any pest for which that species is a host (Greene and Millward, 2016). Once established in urban forests, invaders may expand into surrounding natural forests (Tait et al., 2005; Alvey, 2006).

Urban forests are not just invasion gateways; for some pests, the most noteworthy impacts actually occur in urban forests. For example, Haack et al. (2010) reported that communities in Illinois, Massachusetts, New Jersey, and New York spent more than US$373 million on ALB eradication efforts between 1996 and 2008, primarily for identification and removal of infested trees. Based on data from communities across the USA, Hauer and Peterson (2017) estimated the nationwide impact of EAB on municipal forestry budgets to be US$280.5 (± 79) million annually; typically, municipal governments in invaded communities spent twice as much on tree removal as in communities where EAB was not present. Kovacs et al. (2010) predicted that the expansion of EAB in the eastern USA between 2009 and 2019 would necessitate treatment or removal and replacement of more than 17 million ash (*Fraxinus* spp.) trees – both publicly and privately owned – within invaded communities, at a total cost of US$10.7 billion. Similarly, Sydnor et al. (2007) predicted eventual losses (including losses in landscape value as well as tree removal and replacement costs) of US$1.8–US$7.6 billion in Ohio communities as a result of EAB expansion, while combined losses in Illinois, Indiana, Michigan, and Wisconsin were predicted to reach between US$13.4 and US$26 billion (Sydnor et al., 2011). The potential economic impact of ALB in the USA could be even larger: Nowak et al. (2001b) projected a total value loss of US$669 billion (based on compensatory value of trees) if the insect were to spread to communities throughout the country, as the preferred hosts of ALB represent approximately 30% of all urban trees.

The impact projections in these studies were constrained by a lack of information about the distributions of host trees in the communities of interest. Kovacs et al. (2010) asserted that their estimates could be improved markedly through systematic inventories of the communities' forests. The concept of urban forest inventory, performed according to standard protocols, gained momentum in the mid-2000s with advances in mobile data collection and online management of geospatial data (Abd-Elrahman et al., 2010; Miller et al., 2015), as well as the release of urban forestry software applications such as i-Tree Eco (Nowak et al., 2008b) and i-Tree Streets (Maco and McPherson, 2003; McPherson et al., 2005). (Both applications are included in the freely available i-Tree software suite, http://www.itreetools.org/.) Although these applications are promoted as tools to model potential benefits of urban forests such as improved air quality and reduced building energy use (Maco and McPherson, 2003; Nowak and Dwyer, 2007), the basic inventory information that they collect has clear utility for management, including for invasive forest pests. For example, i-Tree Eco data have been applied in regional, continental, and global analyses of urban forest composition and tree species diversity (e.g., Yang et al., 2015; Blood et al., 2016; Jenerette et al., 2016), both of which affect how those forests respond to invasions or other types of disturbances. Integrating urban forest inventory data with similar data for natural forests would provide a stronger foundation for forest health monitoring and early pest detection, mitigation and control efforts, spread modeling, and risk mapping (Dwyer et al., 2000; BenDor and Metcalf, 2006; Cumming et al., 2008; Venette et al., 2010; Hudgins et al., 2017).

Unfortunately, even in a relatively data-rich country like the USA, there are pronounced data gaps with respect to urban forests, especially in comparison to the far more comprehensive data available for natural forests. For instance, the USDA Forest Service's Forest Inventory and Analysis (FIA) Program performs systematic, annualized inventories of rural forestlands throughout the USA. The annualized FIA plot network includes ≈135,000 forested plots nationwide, which translates to approximately one plot per 2400 ha of natural forest. At this sampling intensity, and because they are distributed systematically across all forestlands (i.e., excluding urban forests), FIA plots can be used to develop regional-scale tree species distribution maps via spatial interpolation and statistical methods (e.g., Iverson et al., 1999; Moisen et al., 2006). In contrast, the FIA Program only recently embarked on urban forest inventories, conducting its first such inventory in 2014 (see Nowak et al., 2016). Furthermore, urban FIA data collection has been proposed for just a limited number (< 100) of relatively large cities (USDA Forest Service, 2016). Upon completion, these efforts will provide consistent measurements of trees in the targeted cities, but will not be sufficiently representative of the thousands of communities, both large and small, across the USA.

Despite its limitations, the urban FIA initiative stands as a significant step forward; prior to this, urban inventory data were not collected systematically in the USA (Roman et al., 2013) or elsewhere, although it is worth noting that communities throughout Sweden recently have begun systematic collection of urban tree data (primarily street tree data) according to standardized inventory protocols (see Östberg, 2013; Östberg et al., 2013). In turn, the lack of systematically collected data has restricted the scale of scientific inquiries regarding urban forests. Indeed, the most extensive analysis of which we are aware (Cowett and Bassuk, 2017) involved street tree data from 275 communities in New Jersey, New York, and Pennsylvania, representing just ≈8% of the populated places identified by the US Census Bureau in those states. Nevertheless, many communities have completed some type of urban forest inventory for local purposes; for our own work, we have compiled more than 1200 inventory data sets from communities across the USA – especially the eastern USA – and Canada. They differ widely in terms of data collection protocols (e.g., complete inventory vs. sampling across land uses) and target tree populations (e.g., street trees vs. all private and public trees), but they comprise a very large and geographically representative compilation of urban forest inventory data – to our knowledge, the largest such compilation ever assembled. Boyer et al. (2016) identified a need for this sort of compilation to address far-reaching research and management questions at a regional scale. The challenge, of course, is determining how to best make use of the data despite their differences.

We present a model-based approach that utilizes existing inventory data from a sampling of North American communities to characterize urban forests of communities across a large portion of the USA for which inventory data were not available. Specifically, for each