Modeling Spatial Establishment Patterns of Exotic Forest Insects in Urban Areas in Relation to Tree Cover and Propagule Pressure

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J. Econ. Entomol. 103(1): 108–118 (2010); DOI: 10.1603/EC09203

ABSTRACT As international trade increases so does the prominence of urban areas as gateways for exotic forest insects (EFI). Delimiting hot spots for invasions (i.e., areas where establishment is likely) within urban areas would facilitate monitoring efforts. We used a propagule-pressure framework to delimit establishment hot spots of a hypothetical generalist EFI in six U.S. urban areas: Chicago, Detroit, Houston, Los Angeles-Long Beach-Santa Ana, New York-Newark, and Seattle. We assessed how urban tree cover and propagule pressure interact to delimit establishment hot spots and compared the location of these hot spots with actual recent U.S. detections of two EFI: the Asian strain of the gypsy moth, *Lymantria dispar* (L.) (Lepidoptera: Lymantriidae), and Asian longhorned beetle, *Anoplophora glabripennis* (Motschulsky) (Coleoptera: Cerambycidae). Using a lattice of 5-km-diameter cells for each urban area, we used the input data (urban tree cover and propagule pressure) to model establishment and Moran's I to delimit hot spots. We used urban population size and the area of commercial-industrial land use as indicators of propagule pressure in the model. Relative establishment of EFI was influenced more by the two propagule pressure indicators than by tree cover. The delimited land use-based hot spots for Los Angeles-Long Beach-Santa Ana and New York-Newark encompassed more of the actual detections of *L. dispar* and *A. glabripennis*, respectively, than the population-based hot spots. No significant difference occurred between hot spot types for *A. glabripennis* detections in the Chicago urban area. Implications of these findings for management and design of monitoring programs in urban areas are discussed.

KEY WORDS invasive species, nonindigenous species, urban forest, emerald ash borer

Urban areas in the United States are defined as densely settled territories with human populations of ≥2,500 (USCB 2000). Urban areas consist of at least one governmental unit such as a city, town, or village, plus adjacent lands. An urban area is often named after its largest city. For example, Chicago corresponds to both an urban area and a city. To support their metabolism, urban areas require a constant supply of energy and materials (Decker et al. 2000). As a result, they have developed the necessary infrastructure to receive, transfer, store, and distribute domestic and international cargo (Rodrigue 1999, Crainic et al. 2004, Hesse and Rodrigue 2004). As international trade intensifies (Hulme 2009), the prominence of urban areas as gateways for the introduction and spread of exotic pests is likely to increase (Colunga-Garcia et al. 2010). This seems to be especially true for exotic forest insects (EFI). In the United States, for instance, the Asian longhorned beetle, *Anoplophora glabripennis* (Motschulsky) (Coleoptera: Cerambycidae), was first detected in New York City, NY, in 1996; Chicago, IL, in 1998; Jersey City, NJ, in 2002; and Worcester, MA, in 2008 (Haack et al. 1997, 2010; Haack 2006). During the past two decades, the Asian strain of the gypsy moth, *Lymantria dispar* (L.) (Lepidoptera: Lymantriidae), has been detected in or near the urban areas of Austin, TX; Los Angeles, CA; Portland, OR; Tacoma, WA; and Vancouver, BC, Canada (Wallner et al. 1995; USDA 2006a,b, 2008; Hajek and Tobin 2009). For both pests, eradication efforts were successful or are ongoing. Another exotic forest pest, the emerald ash borer, *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae), was detected for the first time in the urban area of Detroit, MI, in 2002 (Haack et al. 2002, Siegert et al. 2007). This insect, however, has spread to several other U.S. states primarily as a result of human movement of infested host material, including logs, firewood, and nursery stock (Haack 2006, Poland and McCullough 2006).

The environmental and financial impact of EFI in urban forests can be significant. For example, *A. glabripennis* could reduce forest canopy by 13–68% and cities dealing with this insect may have to spend be-

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tween US$ 72 million to 2.3 billion (Nowak et al. 2001). It is thus imperative to implement monitoring strategies that prevent the establishment and spread of EFI in urban areas. Not all U.S. urban areas may be equally vulnerable to EFI. In fact, only 4–6% of the >3,000 urban areas in the contiguous United States are the primary final destinations for imports commonly associated with EFI (Colunga-Garcia et al. 2009). By focusing monitoring efforts in urban areas identified as being most vulnerable to EFI, allocation of resources can be optimized (Magarey et al. 2009). However, even monitoring a subset of urban areas can still be challenging, especially those with large territories. For example, the Chicago and New York-Newark urban areas are >5,000 and 8,000 km^2, respectively. Therefore, deciding which urban areas need to be monitored is just the first step. The next step is to identify invasion hot spots, which we define as those areas within the selected urban areas where establishment of EFI is likely to occur.

The task of identifying potential establishment hot spots within urban areas may be less daunting than it seems for urban settings that are under heavy propagule pressure (i.e., high likelihood for introduction of exotic insects via imported cargo) because such pressure reduces the complexity of factors involved in establishment of exotic species (Lockwood et al. 2005). In fact, under high propagule pressure, the two principal constraints to establishment are host resource availability and diet breadth of the exotic pest (Cassey et al. 2004, Lockwood et al. 2005, Colautti et al. 2006).

In our previous work (Colunga-Garcia et al. 2009), we used patterns of national freight movement to highlight which urban areas in the United States were most vulnerable to invasions. To develop a better understanding of how propagule pressure and resource availability influence EFI establishment, we selected six of the more vulnerable urban areas from our first study and conducted an analysis with a hypothetical generalist (wide diet breadth) pest. Our goal was to determine the usefulness of propagule pressure in the delimitation of EFI establishment hot spots within those urban areas. Studies on propagule pressure have relied primarily on the use of indicators such as marine ship traffic or various international trade statistics (Lodge et al. 2006). Lack of freight transport data within the urban areas precluded our use of this variable as an indicator of propagule pressure, so we used the size of the human population and the size of the area devoted to commercial/industrial land use as surrogates for propagule pressure. In using these indicators, we assumed that 1) the relative number of EFI arriving with imported products was proportional to the volume of imports, and 2) the demand for imported products within an urban area was proportional to the size of the urban human population or the size of the commercial/industrial land area.

The specific objectives of this study were 1) to assess how urban tree cover (a measure of resource availability) and two different proxies of propagule pressure (human population size and industrial/commercial land area) interact to delimit establishment hot spots for EFI, and 2) to compare the areas identified by the urban population-based hot spots and land use-based hot spots in relation to recent detections of actual generalist EFI.

Materials and Methods

Objective 1. Identification of Establishment Hot Spots. The assumptions we made in this study were that the hypothetical EFI 1) had a wide host range that included both hardwood and conifer tree species, and 2) was unintentionally introduced into urban areas via imported products, which includes associated wood packaging materials such as crating and pallets. These types of wood packaging often serve as a vector in the spread of bark- and wood-infesting insects (Haack 2006, Haack and Petrice 2009, Haack et al. 2010).

Urban Areas. We selected for our analysis the following six urban areas: 1) New York-Newark, located in the states of New York, New Jersey, and Connecticut (8,680 km^2); 2) Chicago, largely located in Illinois (87%), with the remainder in Indiana (5,500 km^2); 3) Los Angeles-Long Beach-Santa Ana, CA (4,320 km^2); 4) Houston, TX (3,360 km^2); 5) Detroit, MI (3,270 km^2); and 6) Seattle, WA (2,470 km^2). Urban area boundaries were extracted from the cartographic file "2000 Urban Areas" (USCB 2001a). These six urban areas were the final destination of 47% of the machinery products, 26% of the nonmetallic mineral products, and 16% of the wood products imported into the United States in 2002 (Colunga-Garcia et al. 2009).

Destination Sites. For each urban area we constructed a lattice of cells (diameter, 5 km) to represent all potential destination sites within an urban area as shown in Fig. 1. This cell diameter was arbitrarily selected to represent an EFI with a maximum dispersal radius of 2.5 km. Dispersal potential of the Asian longhorned beetle, for example, reaches 2.4–2.6 km (Smith et al. 2004). Emerald ash borer females can fly on average 1.7 km (Taylor et al. 2005). Hereafter, we use

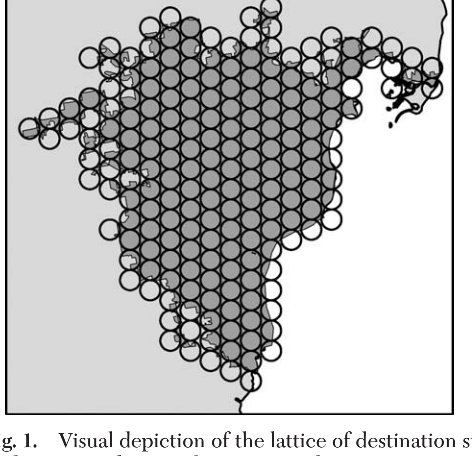

Fig. 1. Visual depiction of the lattice of destination sites (cell diameter, 5 km) in the Detroit urban area.

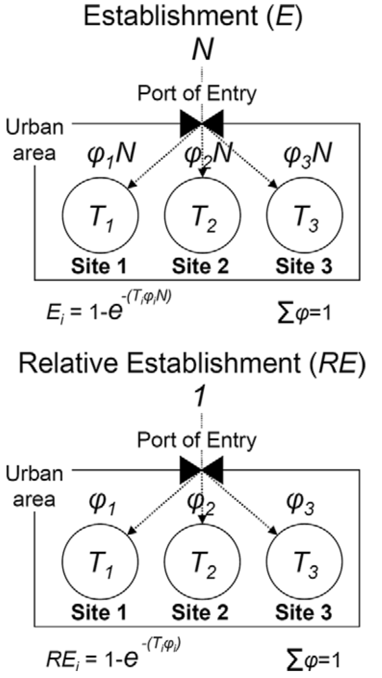

Fig. 2. Parameters used in the calculation of probability of the establishment and the relative establishment of a hypothetical EFI at individual sites within an urban area via international imports. N is the number of EFI introduced into an urban area via international imports, φ is an allocation coefficient for imports, and T is proportion of urban tree cover in a site.

the word "site" to refer to each individual cell within the lattice.

Modeling Establishment in Destination Sites. Jerde and Lewis (2007) developed a propagule based model for invasive species as follows:

$$E = 1 - e^{-(S\phi)} \quad [1]$$

where E is establishment of at least one individual, S is individual probability of survival and ϕ is propagule pressure. This model is similar to the independence model of Leung et al. (2004), where no Allee effects are considered. Building on equation 1, we modeled E_i as the establishment of at least one individual at the i^{th} site as:

$$E_i = 1 - e^{-(T_i\varphi_i N)} \quad [2]$$

In this equation, T_i is the proportion of tree cover in the i^{th} site. We assumed that EFI survival was dependent on the availability of tree cover so we substituted T_i for S in equation 1. $\varphi_i N$ is the propagule pressure in the i^{th} site (i.e., ϕ in equation 1). φ_i is a coefficient to allocate imported products entering an urban area to each i^{th} site ($\sum\varphi = 1$ in each urban area) (Fig. 2). N is the number of EFI introduced into an urban area via imported products (i.e., the propagule pressure for the entire urban area). N can be influenced by many factors, including EFI population levels in the countries of origin, pest survival during transport, ability of EFI to escape detection by inspectors at ports of entry, and type of imported products (NRC 2002, McCullough et al. 2006, Colunga-Garcia et al. 2009). Because we focused on propagule pressure patterns within urban areas, φ_i was more relevant for our analysis than N. Therefore, we set $N = 1$ in equation 2 for all urban areas and estimated relative establishment as follows:

$$RE_i = 1 - e^{-(T_i\varphi_i)} \quad [3]$$

where RE_i is relative establishment for the i^{th} site and the other variables are defined as in equation 2 (Fig. 2).

For this analysis we used two variables as indicators of φ: the size of the urban human population, and the area of the commercial/industrial land use within each urban area. Thus, the final equations used to estimate relative establishment for population-based and land use-based propagule pressure were, respectively:

$$RE_i = 1 - e^{-(T_i P_i)} \quad [4]$$

and

$$RE_i = 1 - e^{-(T_i L_i)} \ldots \quad [5]$$

where P_i is the proportion of the human population in the i^{th} site with respect to the entire urban area population (equation 4), L_i is the proportion of commercial/industrial land use in the i^{th} site with respect to the same type of land in the entire urban area (equation 5), and the other variables are defined as above. To compute P_i, we obtained a rasterized version of the 2000 U.S. population (Seirup and Yetman 2006), which was used in the following equation:

$$P_i = Pop_i/TPop \quad [6]$$

where Pop_i is human population size in the i^{th} site, and $TPop$ is the total human population in the urban area. To estimate L_i, we first computed the area for the high-intensity developed land class at each i^{th} site according to the 2001 National Land-Cover Data (NLCD) (Homer et al. 2004), using the resulting computation in the following equation:

$$L_i = D_{H_i}/TLand \quad [7]$$

where D_{H_i} is the high-intensity developed land area in the i^{th} site, and $TLand$ is the total terrestrial land use in the urban area.

Estimation of Tree Cover. To estimate the proportion of tree cover (T_i) in the i^{th} site, we used the following equation:

$$T_i = Ut_i/L_i \quad [8]$$

where Ut_i is urban tree cover area in i^{th} site and L_i is land area in i^{th} site. To estimate Ut_i, we estimated the greenspace area in developed land (G_i) at each i^{th} site. To estimate G_i, we computed the area for each of the four 2001 NLCD classes for developed land at each i^{th} site. Area values were used in the following equation:

$$G_i = 0.1D_{Hi} + 0.35D_{Mi} + 0.65D_{Li} + 0.9D_{Os} \quad [9]$$

where D_{Hi} is high intensity developed land (80–100% of impervious area); D_{Mi} is medium intensity developed land (50–79% of impervious area); D_{Li} is low intensity developed land (20–49% of impervious area); D_{Os} is open space in developed land (<20% impervious area). Coefficients in equation 9 were obtained by averaging the percentage range of the non-impervious area in each class (i.e., 100 − impervious area) and converting the results to proportions (0–1). Next, using the NLCD, we quantified the forestland area (F_i) at each i^{th} site by adding the area of all forest classes (deciduous, evergreen, and mixed forest) in the i^{th} site. With the results of the above computations, we estimated the urban tree cover area (Ut_i) as:

$$Ut_i = F_i + \psi G_i \qquad [10]$$

where F_i and G_i are defined above, and ψ is an urban area coefficient that determines the proportion of tree cover in G_i. Values of ψ used in this study were 0.27 (Chicago), 0.32 (Seattle), 0.43 (New York-Newark), 0.5 (Los Angeles-Long Beach-Santa Ana), 0.53 (Houston), and 0.78 (Detroit). The ψ coefficients were estimated as follows. First, we obtained literature estimates of tree cover for the largest city in each urban area (see Fig. 4 for the geographic location of the largest city in an urban area). City tree cover estimates used were Chicago, 11.1% (Nowak et al. 1996); Detroit, 31% (American Forest 2006); Houston, 30% (American Forest 2000); Los Angeles, 20.8% (Wu et al. 2008); NY, 16.6% (Nowak et al. 2006); and Seattle, 18% (CSUFC 2007). Second, we converted those percentages to area estimates (i.e., *Ut*). Third, using the NLCD, we estimated both the greenspace area (*G*) (by applying equation 9 to the entire city) and the forestland area (*F*) for each city. Finally, using the values of *Ut, G,* and *F,* we solved for ψ in equation 10 for each city. In using this approach, we assumed that the proportion of tree cover in the developed land's greenspace area (i.e., the ψ coefficient) was constant across the entire urban area.

The relationship between our estimates of urban tree cover and propagule pressure in relation to the full range of *RE* values is shown in Fig. 3. Note that in Fig. 3 only one of the propagule pressure indicators (urban population size) is shown. However, this pattern is applicable to the commercial/industrial land area as well given that both indicators are proportions.

Delimitation of Relative Establishment Hot Spots. We used the Moran's I, a local indicator of spatial association, to detect clusters of sites with high relative establishment potential, or "hot spots" (Anselin 1995, Anselin et al. 2006). This approach essentially detects which establishment values within an urban area are significantly higher than the mean (Fortin and Dale 2005). The desired significance levels ($\alpha \leq 0.05$) of the hot spots were assessed after conducting 9999 permutations using GEODA (Anselin et al. 2006). For brevity hereafter, we use the term "population-based hot spots" when the Moran's I analysis was conducted on relative establishment values resulting from equation 4, and the term "land use-based hot spots" when the analysis was conducted on relative establishment values obtained from equation 5. For both types of hot spots, we quantified the degree of association between

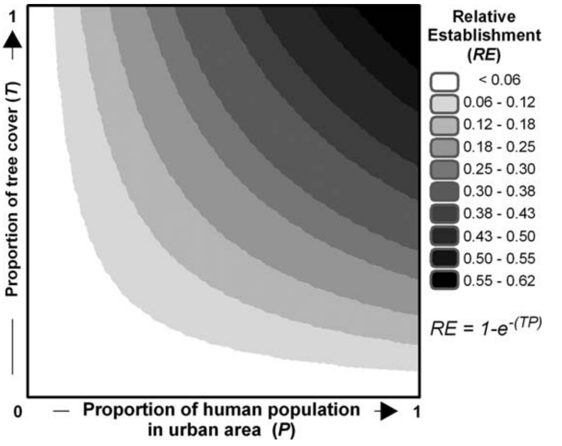

Fig. 3. Relative establishment (*RE*) values at different levels of tree cover (*T*) and urban human population (*P*) (as a proxy for propagule pressure).

urban tree cover (T) and propagule pressure (*P* and *L*) by using the Pearson correlation coefficient (SPSS Inc. 2007). In addition, we analyzed the contribution of urban tree cover and propagule pressure to the relative establishment of the hot spots by conducting linear regression analysis of the form $RE = \beta_0 + \beta_1 T + \beta_2 P$ for the population-based hot spots, and of the form $RE = \beta_0 + \beta_1 T + \beta_2 L$ for the land use-based hot spots (SPSS Inc. 2007). Before regression analysis, we applied the arcsine ($\sqrt{}$) transformation to all relative establishment values.

Objective 2. Comparison of Population-Based and Land Use-Based Hot Spots in Relation to Detections of EFI. We compared both population-based and land use-based hot spots using recent detections of two forest insects in urban areas. The selected insects were the Asian gypsy moth in Los Angeles-Long Beach-Santa Ana and the Asian longhorned beetle in Chicago and New York-Newark. These two EFI were selected because 1) their detection history is well documented; and 2) they attack a wide range of host plants, which is similar to how we based the development of the hot spots on a generalist forest insect. To determine which sites in our lattice (Fig. 1) corresponded to detections of these two insects, we obtained maps detailing detections for the Asian gypsy moth in Los Angeles-Long Beach-Santa Ana area (USDA 2008a) and the Asian longhorned beetle in the Chicago area (USDA–APHIS 2007) and in the New York-Newark area (USDA–APHIS 2008b). Maps were scanned, georeferenced, and overlaid on our lattice. Lattice sites encompassing detection points were recorded as such. In addition, sites were named using the name of the first chronological detection point (e.g., park) within a site, or the place name (e.g., city, borough) that encompassed the site. We distinguished between primary and secondary infestation sites where the former sites were suspected as the original introduction sites, whereas the latter sites were the result of natural or human-assisted dispersal from the primary introduction sites.

Table 1. Regression coefficients (β) and associated statistics for urban population (P) and tree cover (T) in the model $RE = \beta_0 + \beta_1 T + \beta_2 P$

Urban area	Coefficient		SE		t		Significance		CV[a]	
	P	T	P	T	P	T	P	T	P	T
Chicago	1.29	0.08	0.09	0.011	14.2	7.3	<0.001	<0.001	88	51
Detroit	2.51	0.08	0.10	0.006	25.2	13.7	<0.001	<0.001	79	30
Houston	2.00	0.08	0.14	0.011	14.3	7.9	<0.001	<0.001	92	48
Los Angeles-Long Beach-Santa Ana	2.00	0.10	0.11	0.008	17.9	12.4	<0.001	<0.001	78	32
New York-Newark	1.41	0.04	0.12	0.008	12.2	4.3	<0.001	<0.001	123	49
Seattle	1.39	0.07	0.15	0.011	9.5	6.9	<0.001	<0.001	72	47

[a] Coefficient of variation: mean/standard deviation × 100.

We had planned to include the emerald ash borer in our analysis because it is an important invader in one of our selected urban areas, Detroit. Moreover, its host tree (*Fraxinus* spp.) is so widely distributed in the region that any hot spots developed for this insect would probably be similar, for practical purposes, to those of a generalist. However, by the time the insect was first detected in 2002, the invaded area had extended beyond the Detroit urban area. Two primary infestation sites have been identified in the Detroit urban area based on dendrochronological reconstruction analysis (Siegert et al. 2007). Because two sites are not sufficient to conduct meaningful statistical comparisons, we included selected emerald ash borer data for future reference only.

Homer et al. (2004) characterized the commercial/industrial land use class in the 2001 NLCD as highly populated. Consequently, we expected a significant association between urban population size (P) and the area dedicated to commercial/industrial land area (L). To quantify the degree of their association, we used Pearson correlation after arcsine (√) transformation of both variables. Despite the anticipated high association between P and L, we tested whether there was any difference in the number of sites encompassed within the population-based and the land use-based hot spots, using the paired sample t-test (SPSS Inc. 2007). We used the jackknife method (Southwood and Henderson 2000) to obtain as many pseudosamples as there were detections reported for each combination of insect–urban area.

Results

Objective 1. Identification of Establishment Hot Spots. In all urban areas, both propagule pressure indicators (population-based and land use-based) had more influence in determining relative establishment than tree cover (see the magnitude of the regression coefficients in Tables 1 and 2). The higher variability in propagule pressure (among the individual sites within the hot spots) compared with urban tree cover variability (CV; see Tables 1 and 2) is the likely explanation for the greater influence of propagule pressure.

The finding that both propagule pressure indicators played a larger role than urban tree cover in determining relative establishment of EFI can be appreciated visually by comparing the location of the relative establishment hot spots (RE) against the spatial distribution of tree cover (T), population-based propagule pressure (P), and land use-based propagule pressure (L) in Fig. 4. For each of the six urban areas studied, major portions of the hot spots coincided with sites of high human or land use concentration.

The average urban tree cover within most hot spots was less than the average for the whole urban area (Table 3). In the New York-Newark urban area, for example, the average tree cover within the hot spots was 50% less than the average for the entire urban area. For hot spots in the Chicago and Seattle urban areas, the difference was >30%. In addition, within the hot spots of each urban area, there was a significant inverse association ($\alpha < 0.001$) between urban tree cover and the two propagule pressure indicators (r in Table 3). Overall, the number of sites in the hot spots (N in Table 3) averaged 16% of the total number of sites within the urban areas, with a minimum of 9% for the population-based hot spots in the New York-Newark urban area and a maximum of 25% for the land use-based hot spots in the Los Angeles-Long Beach-Santa Ana urban area.

Table 2. Regression coefficients (β) and associated statistics for commercial/industrial land use (L) and tree cover (T) in the model $RE = \beta_0 + \beta_1 T + \beta_2 L$

Urban area	Coefficient		SE		t		Significance		CV[a]	
	L	T	L	T	L	T	L	T	L	T
Chicago	1.39	0.09	0.13	0.014	10.6	6.6	<0.001	<0.001	103	51
Detroit	2.13	0.05	0.16	0.012	13.5	4.2	<0.001	<0.001	99	30
Houston	1.48	0.04	0.18	0.015	8.3	3.0	<0.001	0.005	110	48
Los Angeles-Long Beach-Santa Ana	1.36	0.06	0.14	0.026	10.0	2.2	<0.001	0.029	111	32
New York-Newark	1.25	0.02	0.12	0.009	10.9	2.8	<0.001	0.007	129	49
Seattle	1.39	0.07	0.15	0.011	9.5	6.9	<0.001	<0.001	133	47

[a] Coefficient of variation: mean/standard deviation × 100.

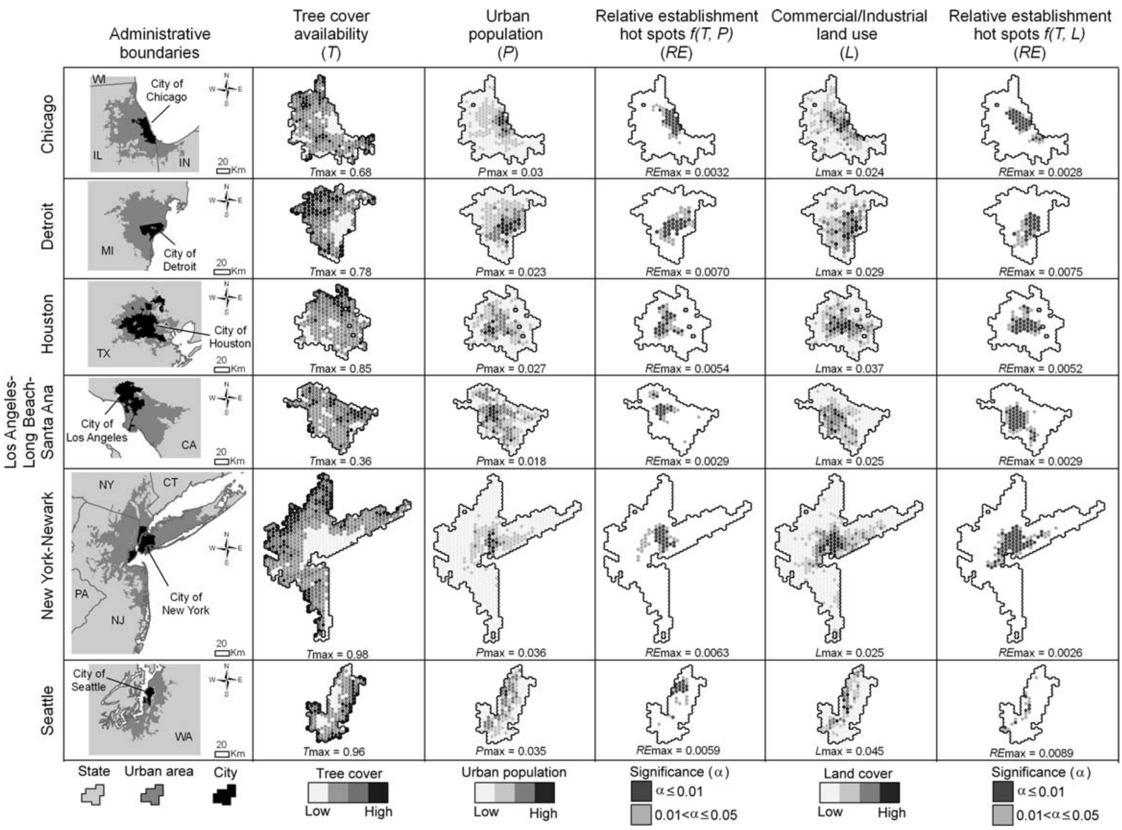

Fig. 4. Distribution of tree cover availability, two propagule pressure indicators (population-based, and land use-based), and relative establishment hot spots for a hypothetical generalist forest pest that could be introduced in urban areas via imported cargo. Classification scales for tree cover and propagule pressure are relative to each map's range of values (see maximum values at the bottom maps) (Jenks 1967, ESRI Inc. 2006). Delimitation of hot spots was made using Moran's I local indicator of spatial association at two significance levels (Anselin et al. 2006).

Objective 2. Comparison of Population-Based and Land Use-Based Hot Spots in Relation to Detections of Actual EFI. A detailed tabulation for the U.S. detection sites of Asian gypsy moth, Asian longhorned beetle, and emerald ash borer in our six selected urban areas is shown in Table 4. The last two columns of the table indicate whether the site was within (+) or outside (−) the hot spot as well as the number of sites (each 5 km wide) away from the edge of the hot spot. The results of the "*t*" test-jackknife analysis showed that the land use-based hot spots encompassed more EFI detections than the population-based hot spots for the Asian gypsy moth in the Los Angeles-Long Beach-Santa Ana urban area (t = 9.8; df = 4; α = 0.001) and the Asian longhorned beetle in the New York-Newark urban area (t = 37.5, df = 17, $\alpha <$ 0.001). In these two cases, the land use-based hot spots encompassed, respectively, 80 and 78% of the detection sites, compared with the 20 and 56% of the population-based hot spots. All primary sites in Los Angeles-Long Beach-Santa Ana and New York-Newark were encompassed by the land use-based

Table 3. Number of sites (*N*), percentage of urban tree cover (*T*) (mean ± SE), and correlation (*r*)[a] of urban tree cover vs two propagule pressure indicators (i.e., urban population size and commercial-industrial land area)

Urban area name	Entire urban area		Pop-based hot spots			Land use-based hot spots		
	N	*T*	*N*	*T*	*r*	*N*	*T*	*r*
Chicago	329	21.4 ± 0.6	44	13.7 ± 0.8	−0.68	48	14.6 ± 0.9	−0.74
Detroit	194	45.4 ± 1.0	45	37.9 ± 1.2	−0.67	37	35.6 ± 1.4	−0.78
Houston	227	31.8 ± 1.0	41	27.5 ± 1.0	−0.63	45	27.4 ± 1.2	−0.74
Los Angeles-Long Beach-Santa Ana	234	19.7 ± 0.4	32	19.8 ± 0.8	−0.66	59	16.8 ± 0.4	−0.90
New York-Newark	580	46.1 ± 0.9	50	22.3 ± 1.7	−0.66	81	20.1 ± 1	−0.78
Seattle	175	41.3 ± 1.5	26	28.7 ± 2.0	−0.74	20	26.7 ± 3.2	−0.58

[a] All correlations were significant at $\alpha < 0.0001$.

Table 4. Detections of four exotic forest insects in four urban areas in relation to establishment hot spots delimited based on tree cover availability and two propagule pressure indicators: urban population size and area of industrial commercial land

Insect and urban area[a]	Detection site name[b]	Yr of detection	Infestation type[c]	Location of detection sites relative to hot spots[d]	
				Pop-based hot spots	Land use-based hot spots
Asian gypsy moth in Los Angeles-Long Beach-Santa Ana	Port of Los Angeles, CA	2003	P	−4	1*
	Orange County, CA	2005	N	−2	1*
	Port of Los Angeles 2, CA	2006	N	−4	1*
	Willowbrook, CA	2007	N	1*	3*
	Rolling Hills, CA	2007	N	−4	−1
Asian longhorned beetle in Chicago	Ravenswood, IL	1998	P	1*	−1
	Addison, IL	1998	S	−3	−1
	Summit, IL	1998	S	−1	1*
	Park Ridge, IL	1999	S	1*	2*
	Loyola, IL	1999	S	1*	−1
	Kilbourn Park, IL	1999	S	2*	1*
	O'Hare airport, IL	2000	S	−1	2*
	Oz Park, IL	2003	S	1*	1*
Asian longhorned beetle in New York-Newark	Greenpoint Brooklyn, NY	1996	P	1*	3*
	Brooklyn 2, NY	1996	P	2*	2*
	Brooklyn 3, NY	1996	P	2*	2*
	Amityville 1, NY	1996	S	−4	−1
	Amityville 2, NY	1996	S	−5	−2
	Lindenhurst, NY	1997	S	−5	−1
	Islip, NY	1999	S	−7	−1
	Ruperts's playground, Manhattan, NY	1999	S	2*	3*
	Flushing, Queens, NY	1999	S	1*	1*
	Bayside, Queens, NY	1999	S	1*	1*
	Woodside, Queens, NY	1999	S	2*	2*
	Luther Gulick Playground, Manhattan, NY	2000	S	1*	2*
	Jersey City, NJ	2002	S	−1	2*
	Kew Garden Hills, Queens, NY	2003	S	1*	1*
	Forest Park, Queens, NY	2003	S	1*	2*
	Carteret, NJ	2004	P	−2	1*
	Linden, NJ	2004	S	−1	1*
	Staten Island, NY	2007	S	−2	1*
Emerald ash borer in Detroit	Garden City, MI	1996	S	2*	1*
	Westland, MI	1996	S	1*	−1

[a] Sources: Asian gypsy moth (USDA 2008a); Asian longhorned beetle (USDA APHIS 2007, 2008b, Sawyer and Panagakos 2009); emerald ash borer (Siegert et al. 2007).
[b] Names indicate a reference to the first detection point (e.g., park) within a site, or a reference to a place (e.g., city, borough) encompassing a site where multiple detections were made (site = cell 5-km diameter).
[c] P, primary infestation/detection; S, secondary infestation (resulting from natural insect spread or human mediated dispersion); N, not able to define.
[d] An asterisk (*) indicates that the detection occurred within a hot spot (outside the hot spot otherwise). The numbers indicate the number of sites, i.e., cells with a 5-km diameter, to the nearest edge of the hot spot; positive numbers increase toward the hot spot center (1 = edge of hot spot), and negative numbers increase away from the hot spots (−1, a site outside but adjacent to the hot spot).

hot spots. The population-based hot spots, however, encompassed only one primary site (Brooklyn) in New York-Newark. No significant difference was found between the population-based and the land use-based hot spots in the case of the Asian longhorned beetle in the Chicago urban area ($t = 0.0$, $df = 7$, $\alpha = 1.000$). Both hot spot types encompassed 63% of the detection sites, although most of the encompassed individual sites differed among the two hot spot types. In fact, only the population-based hot spot encompassed the primary infestation (Ravenswood area) in the Chicago urban area. Regarding the emerald ash borer in the Detroit urban area, both hot spot types encompassed the primary site of Garden City, but only the population-based hot spots encompassed the primary site of Westland City as well.

Several of the Asian longhorned beetle detection sites that occurred outside of the hot spots were immediately adjacent to the land use-based hot spots in the Chicago and New York-Newark urban areas (adjacent = −1). A similar situation was observed in Chicago for the population-based hot spots. The overall distribution of detection sites in relation to both hot spot types is shown in Fig. 5.

Discussion

The results of this study provided important theoretical and applied insights for future programs aimed to prevent EFI invasions in urban areas. First, propagule pressure was more important than urban tree cover in determining the location of establishment hot spots. Employing a propagule-pressure framework would assist managers in delimiting areas where invasions are likely and thereby allow them to optimize resources for EFI monitoring. Including specific data on the number and location of warehouses or nurs-

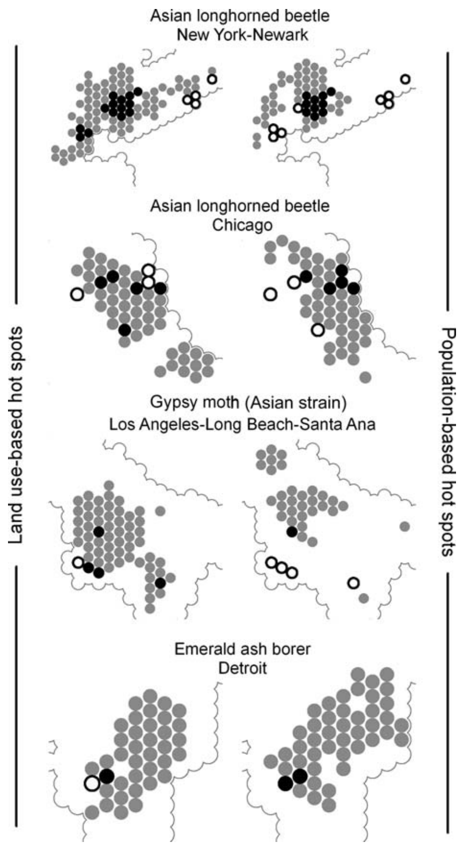

Fig. 5. Detections or establishments of three EFI in four urban areas in relation to population-based and land use-based hot spots (gray, hot spot sites; black, detection or establishment of an EFI within a hot spot: white, detection or establishment of an EFI outside a hot spot).

eries could facilitate further delimitation within the hot spots. The good news about propagule pressure being an important variable in determining areas vulnerable to invasion is that the location of such hot spots is likely to be similar for a wide array of EFI. This finding could facilitate monitoring efforts by allowing personnel and resources to be spatially concentrated. Monitoring these hot spots, however, presents logistical challenges. The predominant land use within the hot spots, judging from our analysis, is commercial-industrial which tends to be highly fragmented and brimming with human activity. Moreover, in commercial-industrial areas there are multiple forest patches ranging in size from single trees to parks or woodlots. Under these conditions it is logical to involve the public in monitoring programs for EFI. However, although it may be relatively easy to involve people in monitoring their own backyards, it will probably require additional effort to systematically involve them in monitoring trees in commercial-industrial areas.

Second, forest cover did not have much effect on determining the location of hot spots in the current study. However, detailed tree species composition could help determine the type of EFI most likely to become established under a propagule-pressure framework. Of interest for the prevention and management of future invasions is the amount of tree cover area in the hot spots. For the urban areas in our study, average tree cover was relatively low in the hot spots when compared with the entire urban area. This fact emphasizes the importance of containing new invasions as early as possible. As newly established EFI disperse beyond the hot spots toward the edge of the urban area, where urban tree cover increases, containing the invasion could rapidly become more difficult or even impossible. Even within hot spots, some urban areas have much more tree cover than others. Therefore, containing invasions in urban areas whose hot spots have high tree cover may be more difficult than in hot spots with less tree cover. Another issue related to the relatively low tree cover in urban hot spots is the increasing awareness that trees provide important ecosystem services to urban areas (Dwyer et al. 2000) and the desire to increase tree cover in many U.S. cities (Galvin et al. 2006a,b; Grove et al. 2006). If this occurs then the hot spots shown in Fig. 4 would be likely targets for tree planting efforts given their relatively low tree cover. Because hot spots are already under heavy propagule pressure, an increase in tree cover could also increase EFI establishment potential. This situation, which is not meant to deter tree planting efforts, emphasizes the importance of increasing tree species diversity to mitigate the impact of any future EFI.

Third, hot spots in urban areas may involve multiple cities, emphasizing the need for collaboration and coordination. For instance, using geographical layers from the U.S. Census Bureau (USCB 2001a,b), we found that the Chicago and New York-Newark urban areas encompass 268 and 671 cities or other governmental units, respectively. Of these, 80 and 188 cities, respectively, intersect the land use-based hot spots that we identified in these two urban areas.

International trade is on the increase (Colunga-Garcia et al. 2009, Hulme 2009), as is the risk of inadvertently introducing EFI in urban areas. In our previous work, we used patterns of national freight movement to highlight which urban areas in the United States were most vulnerable to pest invasion (Colunga-Garcia et al. 2009). Here, we analyzed how propagule pressure affects vulnerability of urban areas to EFI. However, further research on propagule pressure and urban forest cover is needed.

One issue, for example, is the need to increase our understanding on the meaning of propagule pressure indicators in relation to the movement of imported goods in urban areas. The two types of indicators we used, population size and commercial-industrial area, are highly correlated. Thus, the differences noted in how hot spots were delimited likely indicate important nuances in the spatial associations of these two indicators in different urban areas. Perhaps selection of an urban-population cohort (i.e., working age) may enhance the power of the population-based indicator to delimit hot spots. The fact that the population-based indicator performed better in Chicago, whereas the land use-based indicator did better in New York-Newark emphasizes the need for further research on this subject. In the short term, we may need to use both indicators to select hot spots. This could be done by using the indicators separately (as we did in this study) or by developing a model that integrates both. Of course, if data on freight transport or some similar variable (e.g., numbers and locations of warehouses) becomes readily available, there may be no need to explore further the use of the indicators used in our study. However we anticipate that, for the near term, human population or land use data may be the only data available for researchers in many regions of the world to use in these types of investigations.

A second issue relates to the availability of urban forest data. Complete national or regional inventories of urban tree layers may take many years to compile, and ultimately, they may be impractical to establish and maintain (Nowak 2008). In our study, we estimated urban tree cover based on assumptions and procedures that were facilitated by the use of a generalist insect. Assessments for insects with a narrow host range may require different assumptions, and such data may be available only at a very local scale. As forest layers for individual urban areas are developed, there will be a need to analyze their spatial relationship with respect to propagule pressure and compare those results with our findings.

A third issue is the fact that in our model selection we did not include Allee effects (Liebhold and Tobin 2008). In doing so, we assumed that the impact of Allee effects would be minimal under conditions of high propagule pressure. Such an assumption, however, should be revised as future models of EFI establishment and dispersion in urban areas are developed.

More issues are sure to arise as the research on the dynamics of EFI in urban areas progresses; and pursuing a satisfactory answer for them may become a long-term endeavor. Urban forest managers, however, face the short-term challenge of implementing measures to protect local forests. Approaches such as those described in our study may help assist managers with short-term challenges, such as selection of high-risk monitoring sites, while buying time to obtain a more thorough understanding of pest invasions in urban areas.

Acknowledgments

We thank Laura Bix, Eva Kassens, Janice Molloy, Theresa Schultz, Trixie Smith, and two anonymous reviewers for providing comments to enhance this manuscript; Kurt Gottschalk for offering suggestions to improve the analysis; and Chadni Bhan from Michigan State University-Center for Statistical Training and Consulting (MSU-CSTAT) for assisting with statistical analysis. This work was supported by the NRI-USDA/CSREES/Plant Biosecurity Program grant 2006-55605-16658.

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Received 19 June 2009; accepted 30 October 2009.