Freight Transportation and the Potential for Invasions of Exotic Insects in Urban and Periurban Forests of the United States

MANUEL COLUNGA-GARCIA,[1] ROBERT A. HAACK,[2] AND ADESOJI O. ADELAJA[3]

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ABSTRACT Freight transportation is an important pathway for the introduction and dissemination of exotic forest insects (EFI). Identifying the final destination of imports is critical in determining the likelihood of EFI establishment. We analyzed the use of regional freight transport information to characterize risk of urban and periurban areas to EFI introductions. Specific objectives were to 1) approximate the final distribution of selected imports among urban areas of the United States, 2) characterize the final distribution of imports in terms of their spatial aggregation and dominant world region of origin, and 3) assess the effect of the final distribution of imports on the level of risk to urban and periurban forests from EFI. Freight pattern analyses were conducted for three categories of imports whose products or packaging materials are associated with EFI: wood products, nonmetallic mineral products, and machinery. The final distribution of wood products was the most evenly distributed of the three selected imports, whereas machinery was most spatially concentrated. We found that the type of import and the world region of origin greatly influence the final distribution of imported products. Risk assessment models were built based on the amount of forestland and imports for each urban area. The model indicated that 84–88% of the imported tonnage went to only 4–6% of the urban areas in the contiguous United States. We concluded that freight movement information is critical for proper risk assessment of EFI. Implications of our findings and future research needs are discussed.

KEY WORDS nonindigenous species, invasive species, freight analysis framework, exurban forest, wildland–urban interface

International transport of goods is one of the most important human-mediated pathways for the dissemination of invasive pests (Mack et al. 2000, Ruiz and Carlton 2003, McNeely 2006, Meyerson and Mooney 2007). Manufactured and agricultural goods, including associated packaging material and cargo containers, can harbor exotic pests, including exotic forest insects (EFI) (Pasek et al. 2000, NACEC 2003, Meissner et al. 2004, Work et al. 2005, Caton et al. 2006, Haack 2006, McCullough et al. 2006). Port inspections are aimed at detecting and stopping the entry of EFI. In the United States, when high-risk pests are intercepted at ports, reports of those interceptions are stored in electronic databases maintained by the Animal and Plant Health Inspection Service of the U.S. Department of Agriculture (NRC 2002, PPQ 2003, McCullough et al. 2006). This information allows federal and state agencies to implement detection surveys and possible mitigation measures at ports if warranted (McCullough et al. 2006). Given that inspection rates in the United States are <2% (NRC 2002), there is a high potential that some infested cargo will be missed at the ports and be transported to the cargo's final destination. Therefore, it would be valuable to identify the principal final destinations of selected imports that are commonly associated with EFI to aid in regional risk assessments and detection surveys.

Among the several sources of freight transport data available in the United States (FHWA 2004, Mani and Prozzi 2004), the freight analysis framework (FAF) database is one of the most promising to predict the movement of EFI via imports. FAF consists of several data tables for 43 categories of U.S. imports and the within-country flow of U.S. domestic goods (FHWA 2006b). FAF is compiled from multiple data sources in which data gaps are filled using a combination of log-linear modeling and iterative proportional fitting (FHWA 2006a). World regions of origin for the imports in FAF are rather coarse as are the FAF regions within the United States. The latter consist of 63 metropolitan areas and the remaining U.S. territory of entire U.S. states or portions of states.

Economic damage caused by EFI in U.S. forest ecosystems has been estimated at US$2.1 billion/yr (Pi-

[1] Corresponding author: Center for Global Change and Earth Observations, Michigan State University, 205 Manly Miles Bldg., 1405 S. Harrison Rd., East Lansing, MI 48823 (e-mail: colunga@msu.edu).

[2] U.S. Forest Service, Northern Research Station, 220 Nisbet Bldg., 1407 S. Harrison Rd., East Lansing, MI 48823.

[3] Land Policy Institute, Michigan State University, 305 Manly Miles Bldg., 1405 S. Harrison Rd., East Lansing, MI 48823.

mentel et al. 2005). Wood-based crating, dunnage, and pallets have been implicated as a major pathway by which bark- and wood-infesting insects have moved among countries (Pasek et al. 2000). Imports such as tiles, machinery, marble, steel, and ironware have been commonly associated with borer-infested wood packaging material (Haack 2006). For this analysis, we focused on urban areas because as hubs of economic activity (Niemela 1999, Alberti et al. 2003, McGranahan and Satterhwaite 2003) they are the final destination for most imports and thus are at greater risk of EFI introductions. The initial introductions of the Asian longhorned beetle, *Anoplophora glabripennis* (Motschulsky) (Coleoptera: Cerambycidae), in New York, New Jersey, and Illinois (Haack et al. 1997, Haack 2006) and the emerald ash borer, *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae), in Michigan (Poland and McCullough 2006) are prime examples. Forestlands in periurban areas (exurban areas or wildland–urban interfaces) are also at risk of invasions (Hansen et al. 2005, Radeloff et al. 2005). As with the emerald ash borer, once invasive populations establish in urban and periurban areas they are likely to continue spreading into rural areas.

We have been exploring the potential use of FAF data to enhance risk assessment and survey efforts for EFI. In this article, we used regional freight transport information to characterize the risk of urban and periurban areas to EFI introductions via imports. Specific objectives were to 1) approximate the final distribution of selected imports among urban areas of the contiguous United States, 2) characterize the final distribution of selected imports in terms of their spatial aggregation and dominant world region of origin, and 3) assess the effect of the final distribution of selected imports (objective 1) on the level of risk to urban and periurban forests from EFI. We focused our analyses on three categories of imports that have commonly been associated with wood-infesting insects: 1) wood products themselves, and the packaging material associated with imports of 2) nonmetallic mineral products (including marble and ceramic tiles), and 3) machinery.

Materials and Methods

Objective 1. Urban Areas as Final Destinations of Imported Goods. For this analysis, we used the urban areas as delimited by the U.S. Census Bureau (USCB 2003). The world regions of origin of imports used in our analysis were Asia (eastern and southern), Central and South America, Europe, and North America (Canada and Mexico). We used these world regions of origin because, based on preliminary analysis of the FAF database, they were the major regions of origin for U.S. imported wood products, nonmetallic mineral products, and machinery. To approximate the final distribution of these imports among urban areas, we constructed an allocation procedure consisting of two phases. First, we combined the international and domestic FAF transport data to estimate the total amount of each of the three selected imports that arrived in each FAF region in the contiguous U.S. We combined these FAF databases because once imports reach their final destinations according to the FAF international databases they would then become part of the domestic transport flow. Applying the domestic flow rates to the tonnage data from FAF international databases allowed us to project the potential final destination of imports to areas throughout the United States. Once we estimated the amount of imports that arrived in each FAF region (phase 1), we then allocated that particular amount among all urban areas within each FAF region (phase 2). In phase 2, we used the size of the urban population and the rate of truck flow as the criteria to disaggregate the regional FAF tonnage among urban areas.

Combining the International and Domestic Databases (Phase 1). In phase 1, we classified each FAF region into three destination categories depending on their role in the transport of imports: 1) FAF point-of-entry, 2) FAF intermediate destination, and 3) FAF final destination (Fig. 1). A FAF point-of-entry is where imports first arrive in the United States, such as seaports, airports, and border crossings. A FAF intermediate destination is where goods next arrive after passing through the FAF point-of-entry. In the FAF database, our FAF intermediate destinations are listed as the "destination" of the imports. However, we considered these destinations as intermediate destinations because of our assumption that imports become part of domestic transport upon arrival in the United States. FAF final destinations are regions where the imports presumably reach their final destinations via domestic transport (Fig. 1). In the FAF domestic transport database, the "origin" and "destination" regions were, respectively, what we classified as FAF intermediate destination and FAF final destination in our analyses (Fig. 1). Our three destination categories were not mutually exclusive given that any FAF region could serve as one or all of the categories.

We developed the following equation to estimate the tonnage of selected imports to reach the k^{th} FAF region via international and domestic transport:

$$F_k = \sum_{j=1}^{n} \left[\frac{D_{jk}}{TD_j} \sum_{i=1}^{m} I_{ij} \right] \qquad [1]$$

where F_k is FAF estimated tonnage of a selected import to reach the k^{th} FAF final destination; I_{ij} is FAF estimated tonnage of a selected import to be transported from the i^{th} FAF point-of-entry to the j^{th} FAF intermediate destination; D_{jk} is FAF estimated tonnage of a selected import to be transported from the j^{th} FAF intermediate destination to the k^{th} FAF final destination; TD_j is total FAF estimated tonnage of a selected import to be transported from the j^{th} FAF intermediate destination; m is number of FAF points-of-entry; and n is number of FAF intermediate destinations.

In our calculations, we obtained the tonnage estimates by converting FAF's values in short tons to metric tons (1 short ton = 0.9072 metric tons). We

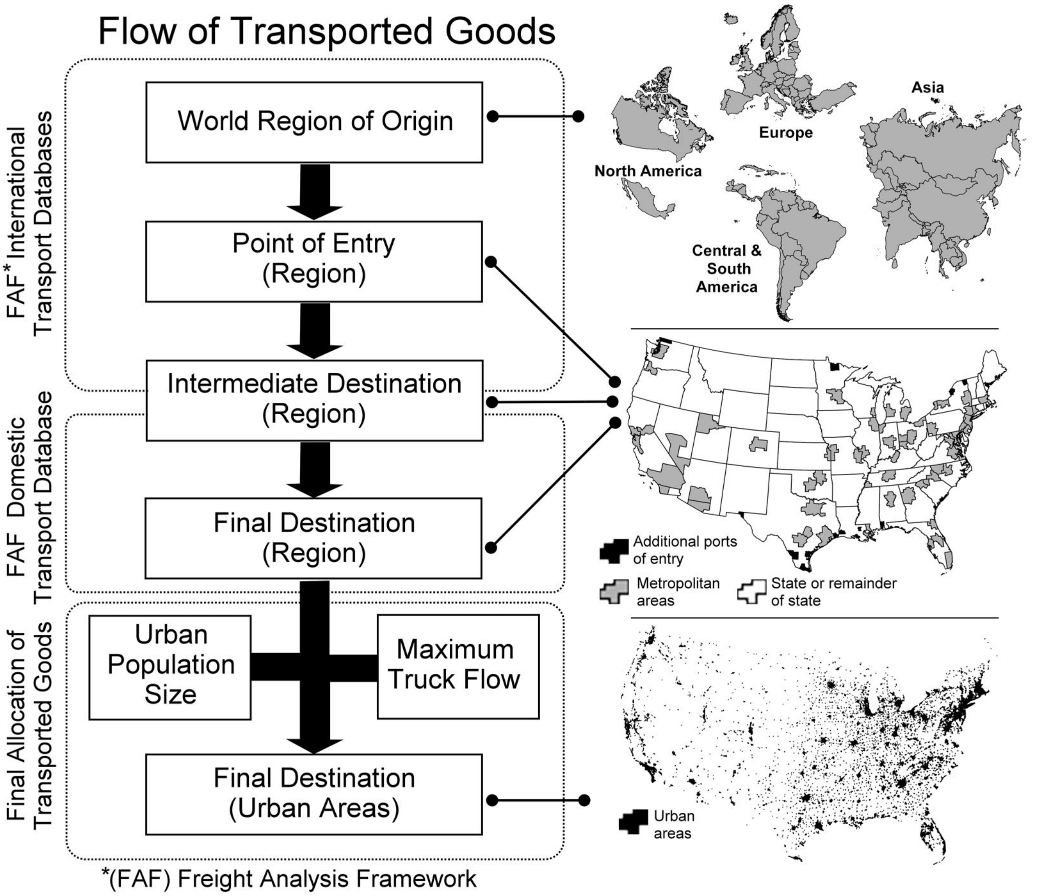

Fig. 1. Visualization of a model to allocate imported goods among urban areas as a function of the international and domestic regional patterns of transported goods, maximum truck flow to urban areas, and urban human population.

pooled the FAF data as to the pathway by which the imports arrived in the United States (i.e., via water and air from overseas origins, and by land from Canada and Mexico). We also pooled the FAF data for the following modes of domestic transportation: truck, rail, water, air, and truck-rail. We did not include goods that were shipped by pipeline, or unknown modes, or shipments that weighed <100 pounds.

Urban Allocation of Goods (Phase 2). We allocated the tonnage of each selected import among the individual urban areas within each FAF final destination (see F_k in equation 1) as a function of total urban population and maximum truck flow, using the following equation:

$$U_{kz} = F_k \times \frac{P_{kz}T_{kz}}{\sum_{z=1}^{N} P_{kz}T_{kz}} \qquad [2]$$

where U_{kz} is tonnage of each selected import to reach the z^{th} urban area of the k^{th} FAF final destination; F_k is FAF estimated tonnage of each selected import to reach the k^{th} FAF final destination (from equation 1); P_{kz} is size of the urban population in the z^{th} urban area of the k^{th} FAF final destination; T_{kz} is maximum truck flow to the z^{th} urban area of the k^{th} FAF final destination; and N is number of urban areas in the k^{th} FAF final destination.

We obtained truck flow data from the "FAF Network" cartographic file and associated data (Alam et al. 2007, FHWA 2007) for 2002, the most recent year for which FAF data were available. To define the urban areas in our analysis, we first updated the cartographic file "2000 Urban Areas" (USCB 2001) with any boundary changes to the urban areas that occurred in 2002 (USCB 2002a, 2002b). We then overlaid both cartographic files (2002 Urban Areas and FAF Network) and selected only those urban areas that intersected the FAF Network. Human population data for each urban area were obtained from the U.S. Census Bureau (USCB 2003). When urban areas corresponded to a prison or military facility (eight cases), they were removed from the analyses and their populations were added to the closest urban area. Where multiple roads (with different truck flow values) intersected a single urban area, we selected the maximum truck flow value reported for that urban area.

Objective 2. Distribution Patterns of Imports among Urban Areas. We determined whether the selected imports had different spatial patterns of final distribution by comparing the level of dispersion of the imported tonnage among urban areas for each import. We also determined the level of dominance of each world region of origin in its contribution to the national import tonnage for the three selected imports.

To measure the level of dispersion of the imported tonnage after reaching the final destination, we used the following index of dispersion (Fotheringham et al. 2000):

$$I = \sum_{z=1}^{N} (U_z - \overline{U})^2 / (N-1)\overline{U} \quad [3]$$

where I is index of dispersion; U_z is tonnage of selected imports reaching the z^{th} urban area; $\bar{U}$ is mean tonnage of selected imports reaching all urban areas; and N is number of urban areas.

This index of dispersion describes distribution patterns as regular, random, or clustered (Fotheringham et al. 2000). Because we expected the imported tonnage to have a clustered distribution (i.e., $I > 1$) among urban areas, we used this index to indicate the degree of clustering for each of the selected goods (i.e., the more clustered the less disperse). We also used two additional indicators of aggregation: 1) the number of urban areas and U.S. states that contributed to the upper 80% of imported tonnage after final delivery, and 2) the largest percentage contribution made by an individual urban area for each of the three selected imports.

To measure the dominance of particular world regions as the source of a selected import, we first determined which world region of origin contributed the greatest amount of tonnage to each urban area. Then we used the Simpson dominance index (Magurran 2004) to calculate the degree to which any world region of origin dominated the U.S. imports. This index was calculated with the following equation:

$$D = \sum_{r}^{W} \frac{V_r(V_r - 1)}{N(N-1)} \quad [4]$$

where D is Simpson's dominance index; V_r is number of urban areas with the r^{th} world region of origin as the dominant region of origin for a particular import; W is number of world regions of origin (four for this analysis); and N is number of urban areas.

Objective 3. Final Distribution of Imports and EFI Risk to Urban and Periurban Forests. We first selected those urban areas that had each allocated at least 0.1% of the total tonnage imported into the United States for each of the selected imports. We assumed that these urban areas would be more likely to receive the imports in their original packaging and thus be at greater risk of EFI introductions. We arbitrarily choose 0.1% as the import threshold that would keep packaging intact given that we found no available information on this topic.

We developed a simple risk model based on the tonnage of selected imports arriving at specific urban areas and their associated urban and periurban forest area. We assumed that if specific imported goods were carrying EFI, then urban and periurban areas with large forestlands would be at higher risk of invasion. The purpose of this analysis was to assess whether different import categories or world regions of origin affected the level of risk to invasion. Because our focus was primarily on trade patterns, we did not consider environmental or biological factors other than forest landcover. The equation we developed for the risk model was the following:

$$R_z = \frac{U_z}{U_{\max}} \times \frac{A_z}{A_{\max}} \quad [5]$$

where R_z is risk of exposure to EFI that could potentially reach the z^{th} urban and periurban forest; U_z is tonnage of selected imports to reach the z^{th} urban area (from equation 2); U_{max} is Highest U_z observed among all urban areas; A_z is forest landcover area (m^2) within and around the z^{th} urban area out to a distance of 3 km; and $A_{\max}$ is highest A_z observed among all urban areas.

Forest landcover area was estimated combining the deciduous, evergreen, and mixed forest classes provided in the 2001 U.S. national landcover database (Homer et al. 2007). We first calculated the forest landcover within each urban area. Then we estimated the periurban forest by calculating the forest landcover area around each urban area out to a distance of three km, considering that a three km buffer would encompass vulnerable forestland in close contact with each urban area. The application of equation 5 to all combinations of the four world regions of origin and the three import categories resulted in 12 risk assessment groups. Within each group, we ranked urban areas for risk (1, highest risk), and using the one-tailed Kendall's tau_b coefficient (SPSS Inc. 2007), we estimated the degree of correlation among all combinations of the 12 risk assessment cases.

Results

Distribution Patterns of Imports among Urban Areas. We approximated the final distribution for the three selected imports in metric tons to 3,126 urban areas in the United States. We observed differences in the spatial aggregation of the imported tonnage. The index of dispersion values were $I = 4{,}699$ for machinery, $I = 648$ for nonmetallic mineral products, and $I = 280$ for wood products. The numbers of urban areas involved in the upper 80% of the imported tonnage were 56 urban areas for machinery, 96 for nonmetallic mineral products, and 138 for wood products. Similarly, the numbers of U.S. states encompassing those urban areas were 22 states for machinery, 28 for nonmetallic mineral products, and 47 for wood products. Finally, the largest percentage contribution by a single urban area to the total import tonnage was 28% for

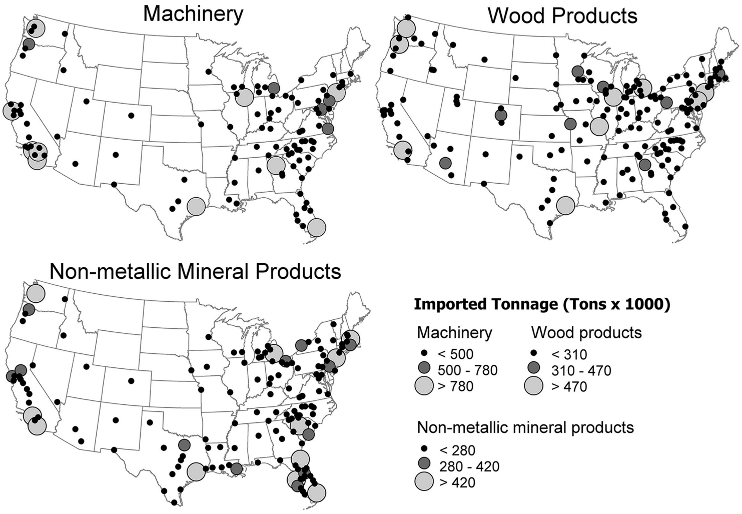

Fig. 2. Modeled final destination (urban areas) and total flow (tons × 1,000) for three categories of imported goods in the contiguous United States for 2002. Only urban areas that received 0.1% or more of all imported tonnage for a given category of imported good are shown. The two upper size classes (circles) in the map labels represent, respectively, the outliers and the extreme outliers based on a box-whisker plot distribution.

machinery and 8.8% for nonmetallic mineral products (Los Angeles/Long Beach/Santa Ana, CA, in both cases) and 3.6% for wood products (Chicago, IL/IN). Therefore, based on the above-mentioned indicators, final delivery of machinery was the most spatially concentrated of the three import categories, whereas wood products was the most evenly distributed. Patterns of world region of origin dominance differed among the three import categories. For machinery, Asia and North America were the dominant world regions of origin for 77 and 19%, respectively, of the urban areas ($D = 0.62$). For nonmetallic mineral products, North America, Asia, and Europe were the dominant world regions of origin for 66, 17, and 15% respectively, of the urban areas ($D = 0.48$). Finally, for wood products, North America was the dominant world region of origin for 99% of the urban areas ($D = 0.99$).

Despite the large number of urban areas used in our analysis ($n = 3{,}126$), final destination of the imports accumulated in relatively few urban areas. Figures 2 and 3 show, respectively, the final destination of the three selected imports and the dominant world region of origin for those urban areas that individually contributed at least 0.1% of the total tonnage within each import category. The number of urban areas in these subsets was 98 for machinery, 148 for nonmetallic mineral products, and 174 for wood products. Although these urban areas received between 84 and 88% of the total import tonnage, they made up only 3.6–5.6% of all 3,126 urban areas. The patterns of import dispersion and world region of origin domi-

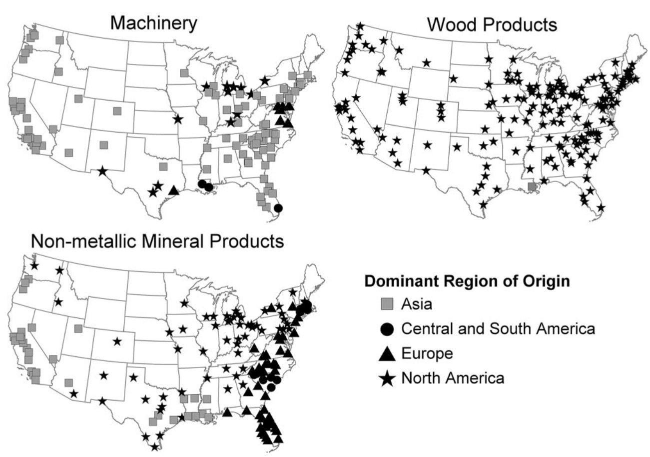

Fig. 3. Modeled final destination (urban areas) by dominant world region of origin for three categories of imported goods in the contiguous United States for 2002. Only urban areas that contributed 0.1% or more to all imported tonnage for a given imported good are shown.

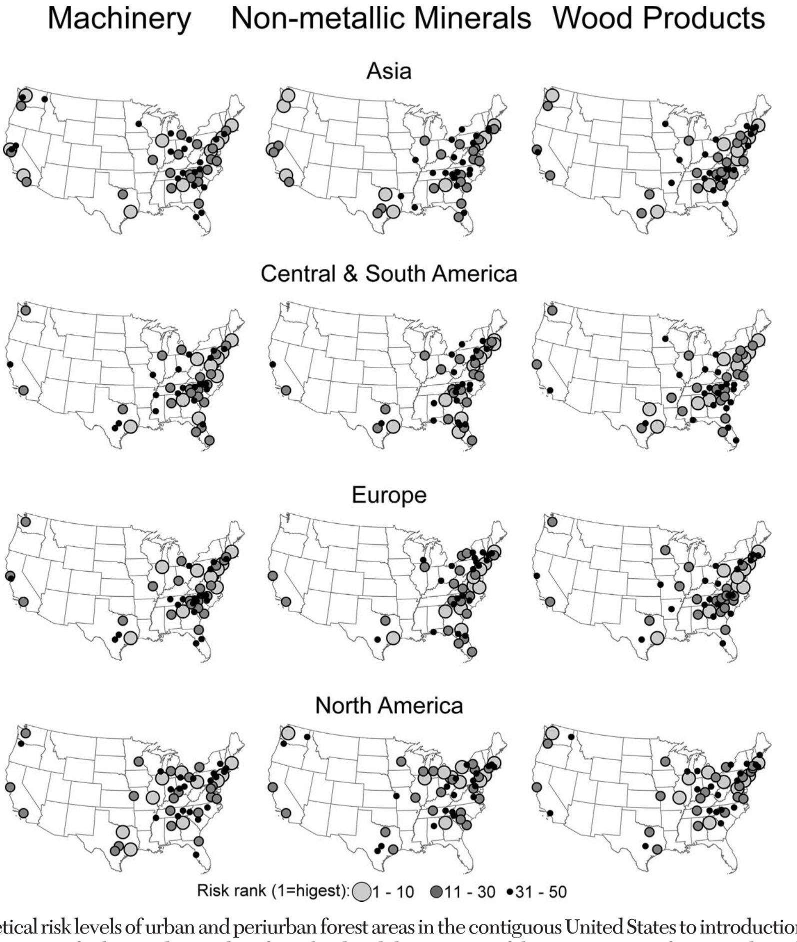

Fig. 4. Hypothetical risk levels of urban and periurban forest areas in the contiguous United States to introductions of exotic insects based solely on the amount of urban and periurban forestland and the tonnage of three categories of imported goods from four world regions (rate of entry of exotic species is assumed to be proportional to the amount of tonnage). The selected imported goods are known to be pathways for the introduction of bark- and wood-infesting insects. Only the 50 urban areas at highest risk are shown.

nance documented above also held for these selected subsets of urban areas. The only major change detected was with respect to the dominant world region of origin for nonmetallic mineral products. North America, Asia, and Europe were still the dominant world regions of origin but for 41, 21, and 30% of the urban areas (D = 0.3), respectively. Figure 2 shows that some urban areas were the final destinations of large amounts of imports regardless of category. Figure 3 shows that Asian imports of machinery and North American imports of wood products dominated across the United States. For nonmetallic mineral products, however, Asia was the dominant world region of origin for most imports delivered to the western United States and some Gulf states (Louisiana and Texas), Europe for the eastern United States, and North America for the Midwest.

Final Distribution of Imports and EFI Risk to Urban and Periurban Forests. The geographic patterns that resulted from the risk model for each of the 12 import × world regions of origin cases are shown in Fig. 4 (only the 50 highest-risk urban areas are shown in the maps). Overall, both the maps (Fig. 4) and the rank correlation tests (Table 1) showed a high level of similarity in the pattern of risk. Highly significant rank correlations ($P \leq 0.001$) resulted from all paired combinations of the 12 import × world regions of origin risk assessment cases depicted in Fig. 4, with correlations ranging from 47 to 85% (100, perfect correlation) (Table 1). Average correlations of the risk-ranking percentages among different imports that originated from the same world regions were 71, 75, 76, and 77% for Asia, Central and South America, Europe, and North America, respectively. Average correlation of risk rankings among the same imports that originated from different world regions were 62, 70, and 77% for machinery, nonmetallic mineral products, and wood products, respectively.

Although the above correlation percentages are for the most part relatively high, the observed differences (100 − the rank correlation percentage) also deserve attention. They reflect differences in risk among the same import products from different world regions of origin or differences in risk among different import

Table 1. Degree of correlation (0–100%) between the risk rankings of urban areas resulting from paired comparisons of 12 risk assessment cases involving three import categories (M, machinery; N, nonmetallic mineral products; W, wood products) from four world regions

	Asia		C. & S. America[a]			Europe			N. America[b]		
	N	W	M	N	W	M	N	W	M	N	W
Asia											
M	74	66	64	63	69	74	59	64	64	65	63
N		74	55	63	66	67	67	67	55	57	61
W			64	72	83	76	70	83	54	54	72
C. & S. America											
M				77	77	85	76	77	63	51	55
N					71	72	85	70	49	47	54
W						76	72	85	57	51	68
Europe											
M							75	80	68	62	62
N								73	51	50	56
W									57	54	70
N. America											
M										80	78
N											73

Model parameters were urban population, urban and periurban forest area, and tonnage of selected imports (rate of entry of exotic species was assumed to be proportional to the amount of tonnage). Only urban areas that contributed 0.1% or more to all imported tonnage of a particular commodity were considered in the analysis. All correlations were significant at the 0.001 level by using the one-tailed Kendall's tau_b.

[a] Central and South America.

[b] Canada and Mexico.

products from the same world region of origin. Several U.S. states along the eastern coast, California and Washington along the western coast, and Texas on the Gulf of Mexico seem to rank consistently high under all import × world regions of origin groupings (Fig. 4). However, the specific risk ranking of individual urban areas varied depending on the import category or world region of origin. For most urban areas in the midwestern Great Lakes states, the risk is highest for imports from North America (Mexico and Canada).

To better appreciate the impact of these differences, we considered the 15 highest-risk urban and periurban areas for each of the 12 import × world regions of origin risk cases (Table 2). Besides the New York-Newark urban area, which was ranked first in all 12 risk cases, only four other urban areas were ranked among the upper 15 areas in each of the 12 risk assessment cases: Atlanta, Philadelphia, Boston, and Houston (Table 2). For the remaining 35 urban areas in Table 2, risk rankings depended upon the type of import and world region of origin. For instance, Seattle and Los Angeles/Long Beach/Santa Ana both had average risk rankings of 21.7. However, they both would be high risk areas for EFI associated with machinery and nonmetallic mineral products originating from Asia (Table 2). Detroit, although placed in the 44th position in Table 2 with an average risk ranking of 43.8, would be at a higher risk for EFI associated with each of the three selected imports when originating from North America. There were 11 urban areas that ranked in the upper 15 in only one of the 12 import × world regions of origin risk cases analyzed (Table 2).

Discussion

Invasive species face multiple challenges during establishment (Mack et al. 2000). However, once successful, they can cause serious economic and environmental impacts (Mack et al. 2000, Pimentel et al. 2005). Urban areas, as centers of economic activity, can play an important role in human-mediated EFI invasions. Urban areas have industrial centers, transportation networks, and storage facilities that facilitate the introduction and dispersion of EFI associated with imports. Similarly, urban areas interact with their periurban natural and managed ecosystems, providing opportunities for EFI to reach those ecosystems.

Although the role of trade and commerce in the dispersion of plant pests is well recognized, research about this role has been minimal. Our results will help fill this information gap. Overall, we found that the type of imports and the world region of origin can greatly influence the final distribution of imported products to urban and periurban areas and thereby help shape the initial distribution of introduced EFI. Incorporating such trade information into risk assessments can help plant health specialists prioritize areas for EFI detection and monitoring programs. Despite the vast number of urban areas found throughout the United States, 84–88% of the tonnage for our three selected imports were distributed to only 4–6% of the urban areas in the contiguous United States. One explanation for the geographical patterns observed in Figs. 2 and 3 was the differences in the degree of movement of imports between the FAF points-of-entry and the FAF intermediate destinations, as well as the domestic movement between the FAF intermediate and FAF final destinations. For example, 84% of the machinery imports from Asia remained within the same state as the FAF point-of-entry, whereas only 22% of the imported wood products from North America did so. With regards to nonmetallic mineral products, 88.6% of the imports from Asia and 86.2% of the imports from Europe remained within the same state as the FAF points-of-entry. Similarly, with regards to domestic movement, the final destination of 80.3% of machinery imports was in the same state as the FAF intermediate destination, followed by 65.6% for nonmineral metallic products and 59.7% for wood products.

Haack (2006) listed 25 exotic bark and wood-infesting Coleoptera that were first found in the contiguous United States from 1985 through 2005. As of September 2008, three more exotic insect borers were reported in the contiguous United States: *Agrilus subrobustus* Saunders (Coleoptera: Buprestidae) in Georgia in 2006 (Westcott 2007), *Sirex noctilio* F. (Hymenoptera: Siricidae) in New York in 2004 (Hoebeke et al. 2005, Dodds et al. 2007), and *Xyleborus maiche* (Stark) (Coleoptera: Curculionidae: Scolytinae) in Pennsylvania in 2005 (NPAG 2006). In Fig. 5, we highlighted the U.S. state where each of the above 28 exotic borers was first reported. We acknowledge that the initial state in which a new exotic species is first found is not always where it was actually first intro-

Table 2. Urban areas in the contiguous United States ranked (1, highest) by hypothetical risk of exposure of their urban and periurban forests to exotic insects via imported products

Urban area[a]	Avg. risk ranking[a]	Risk case (import × world region of origin)											
		C & S. America[b]			Asia			Europe			N. America[c]		
		M	N	W	M	N	W	M	N	W	M	N	W
New York-Newark, NY-NJ-CT	1	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Atlanta, GA	3.3	**2**	**6**	**3**	**3**	**4**	**3**	**2**	**3**	**3**	**2**	**6**	**2**
Philadelphia, PA-NJ-DE-MD	4.5	**4**	**7**	**2**	**5**	**8**	**2**	**3**	**5**	**2**	**7**	**5**	**4**
Boston, MA-NH-RI	6.2	**8**	**2**	**10**	**8**	**10**	**6**	**6**	**2**	**10**	**5**	**4**	**3**
Houston, TX	6.3	**3**	**4**	**5**	**10**	**2**	**5**	**4**	**4**	**5**	**9**	**12**	**13**
Washington, DC-VA-MD	9	**5**	**9**	**4**	**9**	16	**4**	**5**	**7**	**4**	**13**	22	**10**
Pittsburgh, PA	11.1	**10**	21	**7**	18	**11**	**10**	**10**	**13**	**7**	**10**	**10**	**6**
Chicago, IL-IN	14	16	30	18	**7**	17	16	**9**	27	**12**	**3**	**8**	**5**
Baltimore, MD	14.2	**6**	**14**	**6**	**12**	27	**8**	**7**	**14**	**9**	**15**	38	**14**
Dallas-Fort Worth-Arlington, TX	14.3	**12**	16	**9**	**13**	**9**	**15**	**14**	24	21	**8**	**11**	19
Virginia Beach, VA	14.3	**7**	**11**	**12**	**14**	21	**11**	**8**	**10**	**8**	16	30	23
Richmond, VA	17.8	**11**	22	**11**	21	26	**7**	**13**	**9**	**6**	26	34	27
Charlotte, NC-SC	18	**13**	17	16	16	19	18	**11**	16	**13**	28	21	28
Seattle, WA	21.7	22	71	22	**2**	**3**	**9**	22	63	23	**14**	**2**	**7**
Los Angeles-Long Beach-Santa Ana, CA	21.7	30	28	40	**4**	**5**	**12**	19	19	30	23	19	31
San Francisco-Oakland, CA	22	40	47	**15**	**6**	**6**	20	**15**	18	31	24	20	22
Columbia, SC	22.5	17	**8**	23	19	**13**	32	**12**	**8**	18	42	17	61
Jacksonville, FL	26	**9**	**5**	**13**	17	**15**	46	17	**6**	27	27	71	59
Cincinnati, OH-KY-IN	26.5	32	29	31	25	20	37	29	39	39	**11**	**14**	**12**
Birmingham, AL	26.7	18	50	**8**	23	30	**13**	28	56	**14**	25	37	18
Asheville, NC	27.5	24	26	20	28	32	19	23	20	**11**	44	50	33
St. Louis, MO-IL	28.1	34	51	34	**15**	40	36	30	53	17	**6**	**13**	**8**
Cleveland, OH	31.8	37	39	39	34	37	40	33	46	41	**12**	**7**	16
Nashville-Davidson, TN	32.2	26	60	21	29	48	27	31	61	29	18	**15**	21
Providence, RI-MA	33.3	-	**3**	51	-	18	54	-	**11**	50	-	40	39
San Antonio, TX	35.3	38	24	29	62	**12**	29	38	36	37	29	36	53
Springfield, MA-CT	37.4	-	**12**	63	-	46	43	-	32	47	-	31	25
Charleston-North Charleston, SC	37.4	27	**13**	50	31	25	53	20	17	34	61	28	90
Roanoke, VA	38	21	54	24	40	43	**14**	25	21	19	66	69	60
Tampa-St. Petersburg, FL	40.4	19	**10**	19	44	29	65	47	**12**	45	37	80	78
Augusta-Richmond, GA-SC	41.2	46	48	**14**	33	45	24	41	55	26	54	65	43
Minneapolis-St. Paul, MN	41.3	56	81	44	38	56	33	51	70	**15**	20	16	**15**
Detroit, MI	43.8	25	79	70	22	64	84	24	77	64	**4**	**3**	**9**
Worcester, MA-CT	44.1	-	**15**	66	-	61	45	-	38	60	-	33	35
Buffalo, NY	45	60	41	75	68	42	61	55	**15**	66	22	**9**	26
Portland, OR-WA	45.2	70	90	54	**11**	**7**	25	63	68	61	43	39	**11**
Orlando, FL	49.1	**15**	19	41	42	44	72	46	22	56	52	95	85
Miami, FL	57.4	**14**	23	45	57	58	91	52	23	62	70	89	105
Sacramento, CA	62.3	79	94	68	36	**14**	60	56	75	92	58	60	56

Risk model incorporated urban population, urban and periurban forest area, and import data for three categories of goods (M, machinery; N, nonmetallic mineral products; W, wood products) imported from four world regions (rate of entry of exotic species was assumed to be proportional to the amount of tonnage). Numbers in bold highlight the upper 15 rankings (of 3,126 urban areas) in at least one of the 12 import × world region cases).

Only the 15 urban areas at highest risk within each case of risk model are listed. State abbreviations are as follows: AL, Alabama; CA, California; CT, Connecticut; DC, District of Columbia; DE, Delaware; FL, Florida; GA, Georgia; IL, Illinois; IN, Indiana; KY, Kentucky; MA, Massachusetts; MD, Maryland; MI, Michigan; MN, Minnesota; MO, Missouri; NC, North Carolina; NH, New Hampshire; NJ, New Jersey; NY, New York; OH, Ohio; OR, Oregon; PA, Pennsylvania; RI, Rhode Island; SC, South Carolina; TN, Tennessee; TX, Texas; VA, Virginia; WA, Washington.

[a] Arithmetic mean of all 12 import × world region of origin risk-ranking cases.

[b] Central and South America.

[c] Canada and Mexico.

duced. Wood packaging material was the likely pathway by which almost all of these 28 exotic borers first entered the United States (Haack 2006). The 16 highlighted U.S. states in which these 28 borers were first found generally coincide with the states in Fig. 5 that are at relatively high-risk for EFI introductions based on import tonnage and forest landcover. In fact, the states where two or more of the new exotic borers were first found (Fig. 5; California, Florida, Georgia, New York, Pennsylvania, and Texas) contain at least one urban area at high risk for EFI introductions (Table 2).

Work et al. (2005) estimated that 42 exotic insect species may have already entered and become established within the United States between 1997 and 2001. Levine and D'Antonio (2003) conservatively estimated that during 2000–2020, 115 new insect pests and five new plant pathogens will become established in the United States. Our results indicate that there is a high likelihood that EFI could first become established in just four to six percent of the U.S. urban and periurban areas based on freight transport. It is therefore imperative that trade information, in addition to ecological and climatic data, be

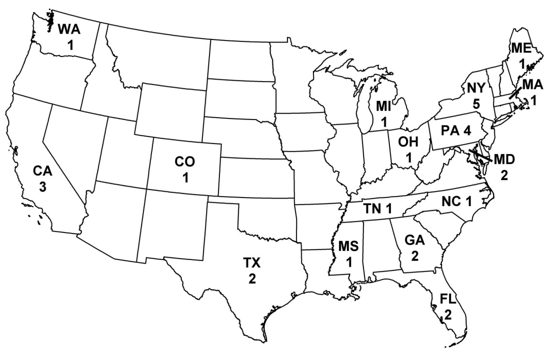

Fig. 5. State map of the contiguous United States showing the number of exotic borers first reported during 1985–2007 (Hoebeke et al. 2005, Haack 2006, NPAG 2006, Westcott 2007). CA, California; CO, Colorado; FL, Florida; GA, Georgia; MA, Massachusetts; MD, Maryland; MI, Michigan; MS, Mississippi; NC, North Carolina; NY, New York; OH, Ohio; PA, Pennsylvania; TN, Tennessee; TX, Texas; WA, Washington.

considered in pest risk assessment and selection of EFI survey sites.

During the course of our analyses, we identified several important questions that require further research. For instance, what is the effect of aggregation or dispersion of the final destination of imported goods on the vulnerability of urban areas to EFI? Imported goods such as machinery were much more aggregated than were wood products. Higher aggregation of specific imports could indicate areas at higher risk of invasion because more individual EFI could arrive in a specific area and thus have a higher likelihood of establishment.

Another important issue to consider relates to wood packaging materials such as crating and pallets. In the existing FAF trade data, the quantity of imported products is usually described in terms of value (dollars) or weight. For imported machinery and nonmetallic mineral products, it is the associated wood packaging that is the important pathway by which EFI are introduced. Knowing how wood packaging (type, number, and size) relates to the value or weight of specific imports would allow enhanced use of the trade databases.

A third issue for investigation relates to development of better methods to determine the final destinations and tonnage of imports. In our analysis, we allocated FAF regional data among urban areas based on urban population size and maximum truck flow. A more efficient method to allocate products could take into account the number and size of warehouses or the rate of growth of urban areas. We also need a better understanding of how goods move from urban to exurban areas or to nearby natural and managed ecosystems.

We expect that our work will enhance efforts to use FAF regional freight data in risk assessment. It could be argued that FAF data are too coarse to be useful. However, with this concern in mind, we purposely separated the points of entry, intermediate destinations, and final destinations in the transportation chain (see equations 1 and 2). Additional databases may be available that can provide more detailed information in terms of imported products, countries of origin, and ports of entry into the United States. Such information could be used in the point-of-entry component of equation 1 and then the FAF flow patterns from equation 2 could be used to model the potential final destination of the products.

Overall, U.S. imports increased by 45% from 1997 to 2003 (Werneke et al. 2005). Future FAF import projections from 2002 to 2035 for the imports we analyzed in this paper (FHWA 2004) estimate nonmetallic mineral products to grow by 151% from Asia, 186% from Europe, 116% from North America (Canada and Mexico), and 183% from Central and South America. Similarly, for the same time period, machinery imports from Asia are expected to grow by 720% and wood products from North America are expected to grow by 184%. To more effectively face the potential threat of increasing EFI introductions given increasing trade volume, we need a better understanding of the linkages between trade and EFI introductions into forest ecosystems. To gain this increased understanding, greater collaboration is needed between biologists and experts in disciplines such as shipping and packaging. Finally, the results of our work may encourage other countries to build databases that document their domestic transport of imported goods to enhance their own efforts in monitoring EFI and minimize the risk of pest invasion.

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