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Enhancing early detection of exotic pests in agricultural and forest ecosystems using an urban-gradient framework

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Abstract. Urban areas are hubs of international transport and therefore are major gateways for exotic pests. Applying an urban gradient to analyze this pathway could provide insight into the ecological processes involved in human-mediated invasions. We defined an urban gradient for agricultural and forest ecosystems in the contiguous United States to (1) assess whether ecosystems nearer more urbanized areas were at greater risk of invasion, and (2) apply this knowledge to enhance early detection of exotic pests. We defined the gradient using the tonnage of imported products in adjacent urban areas and their distance to nearby agricultural or forest land. County-level detection reports for 39 exotic agricultural and forest pests of major economic importance were used to characterize invasions along the gradient. We found that counties with more exotic pests were nearer the urban end of the gradient. Assuming that the exotic species we analyzed represent typical invaders, then early detection efforts directed at 21–26% of U.S. agricultural and forest land would likely be able to detect 70% of invaded counties and 90% of the selected species. Applying an urban-gradient framework to current monitoring strategies should enhance early detection efforts of exotic pests, facilitating optimization in allocating resources to areas at greater risk of future invasions.

Key words: agricultural plant pests; exotic species; forest plant pests; gradient analysis; invasion risk; nonindigenous species; urban influence.

Introduction

The economic losses attributed to exotic plant pests (i.e., arthropods, nematodes, and plant pathogens) in U.S. agricultural and forest ecosystems have been estimated at US $37.1 billion per year (Pimentel et al. 2005). Most invasions are human mediated via international freight transportation and passenger travel (Haack 2006, Liebhold et al. 2006, Hulme 2009). Urban areas are hubs of international transport, serving as both the origin and destination of most domestic freight movement (Colunga-Garcia et al. 2009). In addition, exotic plant species are a major component of plant ecosystems in urban areas (Niemela 1999).

If entry of exotic pests occurs predominantly in urban areas, then agricultural and forest ecosystems near urban areas must be at higher risk for exotic pest introductions. An urban-gradient perspective (McDonnell and Hahs 2008) could provide insight into the ecological processes involved in exotic pest introductions and their subsequent dispersion. Such ecological processes would very likely involve a complex array of biological factors (e.g., reproductive capacity, Allee effects) (Liebhold and Tobin 2008), and human-mediated factors (e.g., freight transportation, import of ornamental plants) (Reichard and White 2001, Hulme 2009).

Identifying and quantifying the variables involved in exotic pest invasions along urban gradients could potentially become a long-term endeavor. However, time is not on our side. Work et al. (2005) estimated that 42 exotic insect species may have already entered and become established within the United States between

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1997 and 2001. Levine and D'Antonio (2003) estimated that from 2000 to 2020, 115 new insect pests and 5 new plant pathogens would become established in the United States. With this in mind, we considered that finding evidence of an urban gradient regarding plant pest invasions could justify both further research on this subject (a long-term task) as well as delimiting areas at high risk to invasion (a short-term task). The objectives of this study were (1) to assess whether ecosystems near urban areas (in relation to an urban gradient) were at greater risk of pest invasions, and (2) to apply this knowledge to enhance early detection of exotic pests.

Methods

Estimation of an urban gradient

To develop an urban gradient (UG), we first constructed an urban-influence index based on two assumptions regarding exotic pest invasions. First is the assumption that the factors that facilitate exotic pest introductions have greater influence in urban areas receiving larger amounts of imported products that are known to harbor invasive species. Second is the assumption that the intensity of these factors is stronger for plant ecosystems located closer to urban areas compared with areas more distant. Data sources and computation of the urban gradient for agricultural and forest ecosystems are detailed in the Appendix A. The resulting UG had 20 levels ranging from 0.5 (high urban) to 10 (low urban). By having each UG level encompass the same amount (5%) of U.S. cropland or forestland (Appendix A: Fig. A3) we avoided the issue that differences in the number of exotic pests were the result of differences in land area available for invasion. Moreover we were able to implicitly establish a null model, where each level had the same probability of being invaded.

Urban gradient of pest invasions

We selected 39 invasive plant pests of economic importance in the contiguous United States that were either reported by the North America Plant Protection Organization (NAPPO) or were listed in the Cooperative Agriculture Plant Survey (CAPS) national survey targets. NAPPO reports include newly introduced pests that may be of immediate or potential danger for the United States or its trade partners (FAO 2002). Because of their potential negative impact, most of these species are subject to thorough surveys by government agencies to document the extent of their presence in the United States. CAPS is a joint Federal and State pest-detection program for exotic plant pests in the United States (Magarey et al. 2009). The CAPS program targets high-priority pests that have been newly introduced into the United States or are not currently present. We compiled, to the best of our knowledge, a list of all U.S. county occurrences for each selected group of pests through July 2009. Names and criteria for the 39 selected pests and information sources are documented in the Appendix B. We counted the number of different pest species reported in each of the 20 UG levels for the two selected ecosystems. We then tested for significant associations between the number of species and UG level using Pearson correlation coefficient (r). Numbers of pest species were normalized using the $\log_{10} + 1$ transformation.

Delimitation of high-risk zones in agricultural and forest ecosystems

To demonstrate the potential application of using an urban-gradient framework to anticipate future invasions, we proceeded to delimit high-risk zones for human-mediated invasions. We considered a high-risk zone to be agricultural or forest lands nearer to the urban end of the gradient (assuming a significant correlation between the urban gradient and the number of exotic pests). We determined "Risk Zone A" as that part of the U.S. cropland (or forestland) where 75% of the selected agricultural (or forest) pests were found. We also determined "Risk Zone B" as that part of the U.S. cropland (or forestland) where an additional 15% of the selected agricultural (or forest) pests were found. Both risk zones were constructed so as to include at least 75% of the counties reported for each pest. We included in the analysis only counties that had ≥ 2 of the 39 selected pests under the assumption that human-mediated factors facilitating the introduction of exotic pests were likely more prevalent in counties that were repeatedly invaded. Details on the methods used to determine the risk zones are provided in the Appendix C. These selection thresholds, although arbitrary, were deemed reasonable for early detection purposes. To measure the efficacy of Risk Zones A and B in detecting invasions, we overlaid all counties in the data set on the risk zones and quantified the percentage of hits (counties inside a risk zone) or misses (counties outside a risk zone). Since the chronology of county detections was not available for most exotic species, we could not fully evaluate the value of the risk zones in detecting first invasions. We quantified, however, the ratio of successes/misses (i.e., a pest was detected within a risk zone or not) and the percentage of successful detections in relation to all county records for a given exotic species.

We tested for the presence of a latitudinal effect on the number of exotic species captured within the agricultural and forest Risk Zone A (i.e., the risk zone that encompassed 75% of the exotic species detections). For each ecosystem we divided the data into 20 latitudinal classes that increased consecutively by 2 degrees. We then conducted a Pearson correlation analysis between the average latitude of each class and the number of exotic species recorded in each class. In addition, we conducted a two-step cluster analysis to identify clusters of species based on the latitudinal gradient (SPSS 2007).

Results

U.S. counties that have been invaded by at least one of the 39 selected pests, and especially those that have

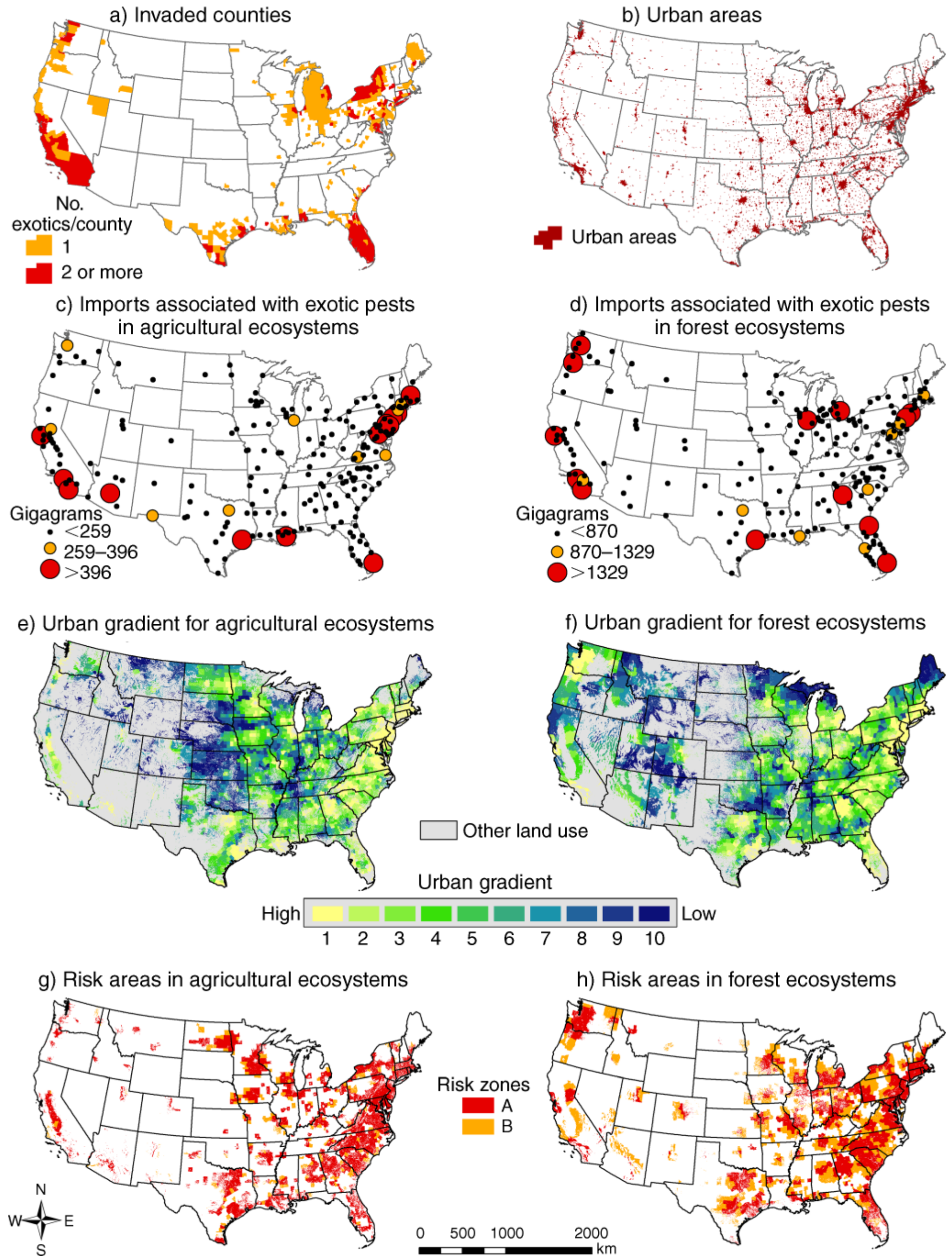

FIG. 1. (a) Distribution of 39 pests based on the positive detection reports for counties of the contiguous United States. (b) Urban areas of the contiguous United States. (c, d) Destination of imported products associated with exotic pests (c) in agricultural ecosystems and (d) in forest ecosystems, by mass (1000 metric tons = 1 gigagram). (e) County-based urban gradient for agricultural ecosystems and (f) for forest ecosystems. (g) Distribution of agricultural areas within two risk zones: Zone A (75% pest detection) and Zone B (an additional 15% pest detection). (h) Distribution of forest areas within the two risk zones.

been invaded by two or more pests, are predominantly located in coastal states (Fig. 1a). This finding not only reflects the fact that large urban areas are common in coastal states (Fig. 1b), but also that those urban areas are the destination of most imports associated with exotic agricultural (Fig. 1c) and forest (Fig. 1d) pests. The maps showing U.S. imports (Fig. 1c, d) indicate the likely destination of 90% of the selected imported products (see Appendix A). To provide a sense of the variability in import volume, the two upper size classes (circles) in both maps represent, respectively, the outliers and the extreme outliers based on a box-whisker plot distribution. Differences in the urban-gradient patterns between agricultural (Fig. 1e) and forest (Fig. 1f)

TABLE 1. Summary of exotic species analyzed, organism type, their target ecosystem, latitudinal cluster, and ratio and percentage of successful detections for all reported counties in the contiguous United States for two risk zones.

Pest species	Organism type†	Target ecosystem‡	Latitudinal cluster number§	Invaded counties¶,|| Zone A Ratio	Zone A Percentage	Zone A + B Ratio	Zone A + B Percentage
Asian gypsy moth, *Lymantria dispar*	I	F	2	7/0	100	7/0	100
Asian longhorned beetle, *Anoplophora glabripennis*	I	F	2	12/0	100	12/0	100
Asiatic citrus psyllid, *Diaphorina citri*	I	A	1	37/22	63	42/17	71
Brown marmorated stink bug, *Halyomorpha halys*	I	B_a	2, 3	42/8	84	44/6	88
Chilli thrips, *Scirtothrips dorsalis*	I	A	1	26/6	81	27/5	84
Chinese longhorned beetle, *Hesperophanes campestris*	I	B	1, 2	1/0	100	1/0	100
Chrysanthemum white rust, *Puccinia horiana*	F	A	2	43/9	83	46/6	88
Citrus greening, 'Candidatus Liberibacter asiaticus'	B	A	1	32/8	80	33/7	83
Citrus longhorned beetle, *Anoplophora chinensis*	I	B	1, 2	2/0	100	2/0	100
Emerald ash borer, *Agrilus planipennis*	I	F	4	101/84	55	148/37	80
European hardwood ambrosia beetle, *Trypodendron domesticum*	I	F		0/1	0	0/1	0
European shot-hole borer, *Xyleborus similis*	I	F	1	1/0	100	1/0	100
False codling moth, *Thaumatotibia leucotreta*	I	B	2, 1	1/0	100	1/0	100
Fruit tree tortrix, *Archips podana*	I	B		0/1	0	0/1	0
Geranium southern bacterial wilt, *Ralstonia solanacearum* R3 B2	B	A	2	9/2	82	10/1	91
Gladiolus rust, *Uromyces transversalis*	F	A	1	5/1	83	5/1	83
Golden nematode, *Globodera rostochiensis*	N	A	2	8/1	89	8/1	89
Guava fruit fly, *Bactrocera correcta*	I	A	1	7/0	100	7/0	100
Japanese cedar longhorned beetle, *Callidiellum rufipenne*	I	F	3	17/1	94	18/0	100
Light brown apple moth, *Epiphyas postvittana*	I	B_f	2, 2	9/6	60	12/3	80
Lobate lac scale, *Paratachardina pseudolobata*	I	F	1	10/0	100	10/0	100
Medfly, *Ceratitis capitata*	I	A	1	7/0	100	7/0	100
Mediterranean pine engraver, *Orthotomicus erosus*	I	F	1	1/9	10	6/4	60
Mexican fruit fly, *Anastrepha ludens*	I	A	1	6/3	67	7/2	78
Oriental fruit fly, *Bactrocera dorsalis*	I	A	1	12/1	92	13/0	100
Pale potato-cyst nematode, *Globodera pallida*	N	A	2	1/1	50	1/1	50
Panicle rice mite, *Steneotarsonemus spinki*	M	A	1	4/1	80	4/1	80
Peach fruit fly, *Bactrocera zonata*	I	A	1	2/0	100	2/0	100
Pink hibiscus mealybug, *Maconellicoccus hirsutus*	I	B_a	2, 1	32/8	80	32/8	80
Plum pox virus, PPV	V	A	2	4/1	80	4/1	80
Red palm mite, *Raoiella indica*	M	F	1	5/0	100	5/0	100
Redhaired pine bark beetle, *Hylurgus ligniperda*	I	F	2	10/0	100	10/0	100
Sirex woodwasp, *Sirex noctilio*	I	F	3	19/22	46	34/7	83
Soybean rust, *Phakopsora pachyrhizi*	F	A	1	11/11	50	11/11	50
Striped snail, *Cernuella virgata*	S	A	2	1/0	100	1/0	100
Sudden oak death, *Phytophthora ramorum*	F	F	2	37/17	69	44/10	81
Swede midge, *Contarinia nasturtii*	I	A	2	19/9	68	23/5	82
Tomato yellow leaf curl, TYLCV	V	A		0/1	0	0/1	0
Yellow-horned horntail, *Urocerus gigas flavicornis*	I	F		0/1	0	0/1	0
Total				541/235	70	638/138	82

† Key to abbreviations: B, bacterium; F, fungus; I, Insect; M, mite; N, nematode; S, snail; V, virus.

‡ Key to abbreviations: A, agricultural ecosystems; F, forest ecosystems; B, both; B_a, county detection was higher in agricultural ecosystems; B_f, county detection was higher in forest ecosystems.

§ Latitudinal clusters. Two clusters for agricultural ecosystems (1, 30.3° N; 2, 41.1° N) and four clusters for forest ecosystems (1, 28.7° N; 2, 39.9° N; 3, 40.9° N; 4, 41.2° N). Only organisms detected in the risk zones were considered; thus the tomato yellow leaf curl and the yellow-horned horntail were excluded from cluster analysis. If the organism is found in both ecosystems, then the first number refers to the agricultural cluster.

¶ Definitions: Ratio = successes/misses (i.e., a pest was detected within a risk zone or not); Percentage = (successes/total counties reported) × 100.

|| Definitions: Risk zone A, detection of 75% of pests; risk zones A + B, detection of 90% of pests (see Fig. 2b, c).

ecosystems depended on the availability of each type of land cover, how close these areas were to urban areas within each county, and the amount of imports as well as their final destination.

Urban gradient of invasions

Overall, one or more of the 39 selected exotic pests (Appendix B) were found in 504 counties in 36 of the 48 contiguous U.S. states. There were 357 counties with just one of the selected exotic pests, and 147 counties with two or more of the selected pests. Descriptive statistics for the number of exotic pests per county were: mean = 1.5 pests, median = 1 pest, and range = 1–9 pests. Of the 39 selected pests, 19 were agricultural pests, 13 were pests of forest or ornamental trees, and seven species were pests of importance for both ecosystems

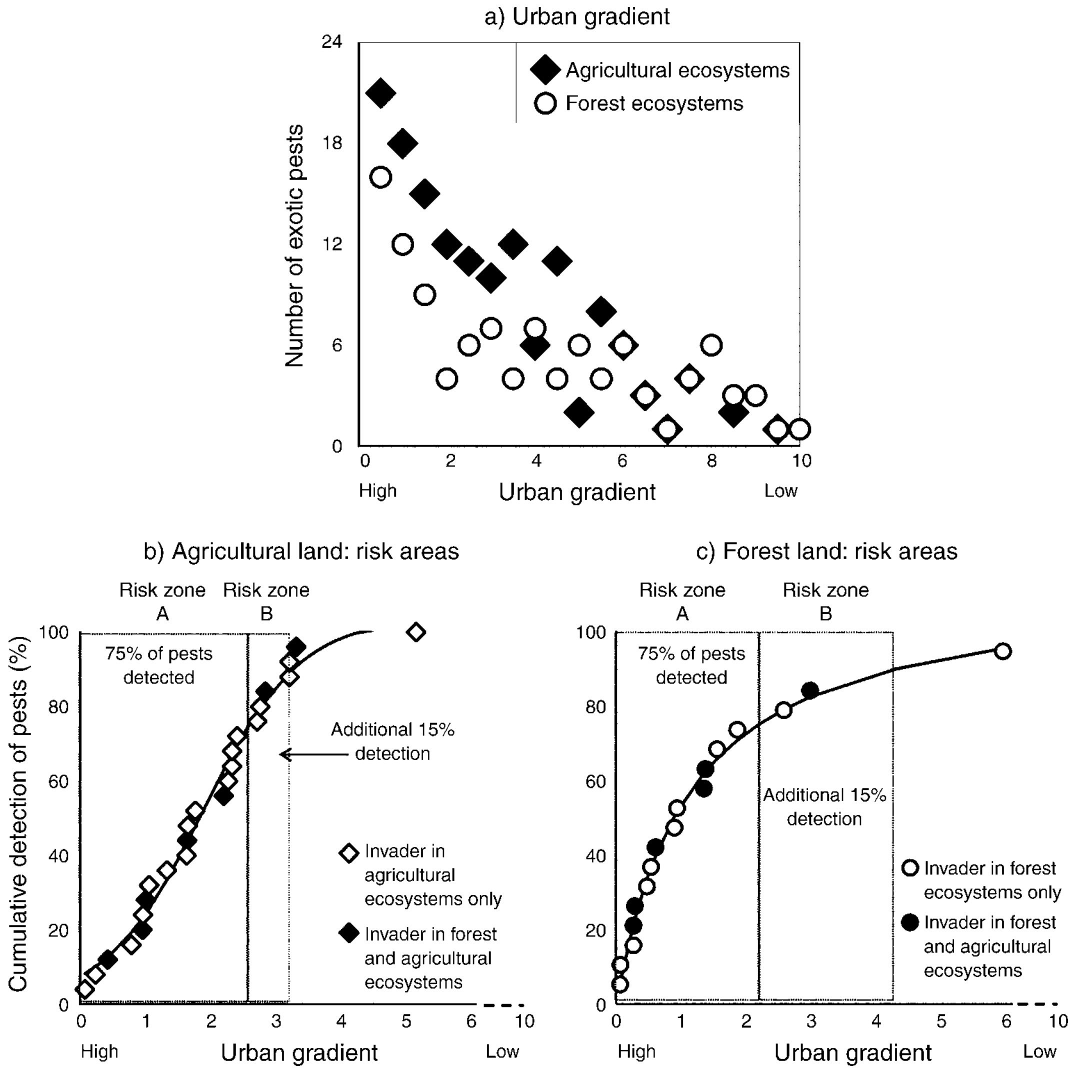

FIG. 2. (a) Number of exotic agricultural and forest pests (of 39 selected pests) along an urban–rural gradient. (b) Delimitation of risk zones for invasions based on the cumulative detection of 75% (Risk Zone A) and an additional 15% (Risk Zone B) of exotic agricultural pests. Pest values represent the third quartile (or the maximum value if less than four counties reported) of all counties reported for a specific pest. (c) Delimitation of risk zones for invasions based on the cumulative detection of 75% (Risk Zone A) and an additional 15% (Risk Zone B) of exotic forest pests.

(Table 1). Highly significant associations occurred between the number of exotic pests reported within each UG level and the urban end of the gradient for both agricultural ($r = -0.9$, $P < 0.001$) and forest ecosystems ($r = -0.82$, $P = 0.001$) (Fig. 2a).

Delimitation of high-risk zones in agricultural and forest ecosystems

The curve that best fits (Kolmogorov-Smirnov $d = 0.01$; $P = 1.00$) the relationship between the cumulative percentage of agricultural species detected "y" and UG "x" as a continuous variable was $y = 103.9/(1 + 12.7e^{-1.4x})$. With this model, we estimated the UG interval for Risk Zone A to be $0 \leq A \leq 2.56$ and for Risk Zone B to be $2.56 < B \leq 3.23$ (Fig. 2b). For forest ecosystems, the fitted curve $y = 113.4x/(1.1 + x)$ ($d = 0.01$; $P = 1.00$) resulted in the UG intervals $0 \leq A \leq 2.15$ for Risk Zone A and $2.15 < B \leq 4.23$ for Risk Zone B (Fig. 2c). Agricultural Risk Zones A and B encompassed respectively 25.6% and 6.7% of the U.S. agricultural land (Fig. 1g). Forest Risk Zone A encompassed 21.5% of the U.S. forest land (Fig. 1h), which was broadly similar to agricultural Risk Zone A. However, forest Risk Zone B covered an additional 17.2%, which is more than double the area covered by agricultural Risk Zone B. Overall, 35 of the 39 species (90%) were "detected" after overlaying all county reports on a combined map for both agricultural and forest Risk Zone A (Table 1). That number remained unchanged even when we added the area for Risk Zone B. Regarding the number of counties where the pests were reported, 71% of the invaded counties (for both agricultural and forest pests) were "detected" within Risk Zone A and 79% were within Risk Zones A and B combined.

No significant latitudinal effect was found for the number of established pests within Risk Zone A for either the agricultural ($r = -0.52$, $P = 0.08$) or forest ($r = 0.34$, $P = 0.27$) ecosystems. However, cluster analysis differentiated "northern" from "southern" pest species in the agricultural ecosystems with latitudinal centroids of 41.1° N and 30.3° N, respectively. Four groups were identified among the forest pests: one "southern" group (centroid = 28.7° N) and three "northern" groups with centroids at 39.9° N, 40.9° N, and 41.2° N.

Discussion

The strong associations found between higher numbers of exotic pest occurrences and the urban end of the urban gradient demonstrate the important role that humans play in pest introductions as well as their likely dispersion. The differences noted between agricultural and forest ecosystems in the distribution of individual pest species along the urban gradient indicated that factors driving invasions vary in their zone of influence away from the urban end of the gradient. For example, although the size of Risk Zone A was similar between the agricultural and forest ecosystems, the size of Risk Zone B was much larger for forest ecosystems (Fig. 2b, c). This means that the initial introduction of some exotic forest species occurs further from the urban end of the gradient compared with agricultural pests. The factors behind these patterns needs to be investigated and elucidated if early detection efforts are going to be implemented effectively. Exurban development has the potential to bring infested material directly to the core of sensitive ecosystems (Hansen et al. 2005). Similarly, recreational travel can move infested plant material, such as firewood, into rural areas, including campgrounds and national parks (Haack et al. 2008) (the role of these two factors, however, is more commonly associated with dispersing organisms after they have been introduced elsewhere).

When we initially conducted the latitudinal analysis, we were expecting to find a large number of species in the southern United States as a result of benign climatic conditions favoring pest establishment. As described in *Results* (above) however, no significant differences were found in terms of number of established species, but differences did exist between the types of species that established at different latitudes. Therefore, determining which species to target in monitoring efforts is just as important as delimiting the monitoring zones.

Further refinement in the methodology to characterize urban gradients is needed. We used the county as the unit of analysis because of the availability of public pest records at that scale. Although the index calculations only took into account the area of crop land or forest land within a county (Appendix A: Fig. A1), the shape of some western counties made it difficult to accurately characterize their urban gradient. Counties in the eastern United States are fairly regular in shape and size and thus were better characterized by our urban gradient. Nevertheless, our approach proved useful to identify critical areas of concern for invasive plant pests. Future research that focuses on high-risk regions could use point-based records of invasive pests if available (i.e., from individual traps). Finer sampling resolution would allow the use of a more elaborate urban gradient based on landscape measurements (Alberti et al. 2001) to provide better insight on the dynamics of human-mediated invasions.

There is clearly a need for further research to more fully understand the ecological processes that facilitate the introduction and subsequent dispersion of exotic plant pests in agricultural and forest ecosystems. The patterns observed in the present study, however, strongly suggest that an urban-gradient framework can be applied to enhance early detections of exotic pests. Inspections at U.S. ports of entry are the first line of defense against exotic pests (Plant Protection and Quarantine 2007). However, because of the sheer volume of imports, <2% of U.S. imports are actually inspected (NRC 2002). When exotic pests bypass port inspections and gain access to agricultural or forest ecosystems, early detection becomes the second line of defense (Wheeler and Hoebeke 2001; Magarey et al. 2009). These survey efforts, however, are full of challenges because of the myriad of potential pests, host plants, and large land areas involved.

Our risk-zone analyses (Figs. 1g, h and 2b, c) showed the potential to prioritize surveillance of agricultural and forest areas based on the association between recent pest invasions and the urban gradient. Such prioritization would facilitate optimum resource allocation in national monitoring programs for exotic plant pests. Although Risk Zone A encompassed 21% of the U.S. forest land and 26% of the U.S. agricultural land, it accounted for 70% of the invaded counties and 90% of the 39 selected pest species. In applying a risk-zone framework, however, three issues must be kept on mind. First, the suggested approach is designed as a tool to gain time while improving our understanding of the invasion process. Such an approach should be continuously updated, or replaced, as new knowledge becomes available. Second, our urban-gradient analysis focused on human-mediated invasions of recently introduced plant pests. For early detection purposes, further analyses are required to investigate the relationship of the urban gradient with those invasive pests that are already established in large portions of the United States (e.g., the European gypsy moth, *Lymantria dispar*) or with exotic plants. Serious thought about collection bias should also be considered (i.e., the association with urban centers is an artifact of higher reporting in more populated areas). To reduce the risk for such bias in our analysis, we focused on pest species where concerted efforts were made by federal and state agencies to conduct regional or national surveys. And third, when prioritizing survey efforts it should be kept in mind that 10% of the pests species that we analyzed were not detected within Risk Zones A and B (Table 1), suggesting the need for some type of survey outside our proposed risk zones.

Our rationale to delimit risk zones (Fig. 2b, c) assumed that the set of exotic pests selected represented a good profile of future threats. Nevertheless, such a rationale is still a working hypothesis that requires further testing. This is the kind of hypothesis, however, that can only be corroborated through careful documentation of future invasions, which can be a costly endeavor given the potential impact and expense of control efforts for certain pests. We propose that our assumptions and findings merit further analysis, especially by federal and state agencies involved in pest-detection programs. These agencies may have access to more specific data on interceptions and pathways that can be analyzed in the context of an urban gradient.

It is important to consider that not all positive associations between invasions and the urban end of the gradient imply a causal relationship with urban areas. In some cases, the association may result from population centers in coastal areas being located in the direct path of atmospheric events such as storms or hurricanes (southeastern United States). For example, soybean rust, a pathogen that entered the United States via atmospheric pathways (Isard et al. 2005), was encompassed by our agricultural risk zones (Table 1). Nevertheless, early detection strategies can still take advantage of the urban-gradient association to design sampling efforts for exotic pests in such regions.

If agricultural and forest areas at the urban end of the urban–rural gradient are at greater risk of invasion, as our findings suggest, then monitoring efforts required to detect future invasions face many challenges. For example, urban and nearby ecosystems tend to be highly fragmented with many ownerships involved, and with many plant species present, which are often on private property. Investigating ways to better involve public participation in monitoring efforts will be a worthwhile investment and perhaps one of the best strategies to provide an economical and efficient solution for early detection of exotic invasive pests.

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APPENDIX A

Description of data sources and computation of the urban gradient for agricultural and forest ecosystems (*Ecological Archives* A020-007-A1).

APPENDIX B

Description of the criteria for the selection of pests, including names and information sources (*Ecological Archives* A020-007-A2).

APPENDIX C

Description of the process to determine the risk zones (*Ecological Archives* A020-007-A3).