



Contents lists available at [ScienceDirect](http://ScienceDirect)

## Landscape and Urban Planning

journal homepage: [www.elsevier.com/locate/landurbplan](http://www.elsevier.com/locate/landurbplan)



# Distribution of invasive plants in a spatially structured urban landscape

Paul Z. Gulezian\*, Dennis W. Nyberg

Department of Biological Sciences, University of Illinois at Chicago, 3452 SES M/C 066, 845 West Taylor Street, Chicago, IL 60607, United States

### ARTICLE INFO

#### Article history:

Received 10 February 2009  
Received in revised form 29 October 2009  
Accepted 24 December 2009  
Available online xxx

#### Keywords:

Alliaria  
Urbanization gradient  
Invasive plants  
Urban ecology  
Vacant lots  
Land use

### ABSTRACT

Plants that are invasive in conservation land also exist as 'wild' elements within planned urban landscapes. We investigated the relationship of the abundances of 10 invasive species to variables of urban spatial structure [land use (houses, apartments, commercial/industrial, or vacant), impervious surface, distance from city center, distance from forest preserve, income] at an individual block scale of analysis. Eighty blocks (about 2 ha each) distributed along a 15-mile (24 km) transect from the center of Chicago, IL, USA west to the county line were inventoried for abundance of three woody species, five biennial forbs and two grasses. Nine of the ten invasive species were found, with an average of 2.74 of our 10 species per block. Collectively, abundance was negatively related to percent impervious surface, and presence was negatively related to local income. No invasive species' abundance was structured by distance and only one of the 10 species, burdock, had any significant correlations with land use. This general lack of connection to urban land use is surprising and suggests most plant species find opportunities for colonization and reproduction independent of land use in the built urban environment. There is also evidence that the built urban environment may be a sink for these invasive plant species, with populations in forest preserves sending more propagules into the built environment than they receive from it.

Published by Elsevier B.V.

### 1. Introduction

Plant species labeled as invasive have a diversity of life cycles, habitats and other attributes. Ecologists have found that invasive plant species do not share a common suite of attributes that underlie their invasive abilities (Rejmanek and Richardson, 1996), and successful invasions proceed through many different mechanisms (Levine et al., 2003; Duda et al., 2003). Recently, attention has shifted from species able to invade agricultural land to species able to displace native vegetation in natural areas (Coblentz, 1990; Huxel, 1999; Chittka and Schurkens, 2001; Sakai et al., 2001; Heger and Trepl, 2003) where such species have become a major focus of land management (Schmitz and Brown, 1994; Pimentel et al., 2005). We label such species 'ecologically problematic' and investigated their status in the urban environment. The urban environment could be a source of ecologically problematic species or it might merely be the recipient of propagules from natural areas. Plant invasion is said to be promoted by disturbance (Anderson et al., 1996; Sanderson et al., 2002; Hierro et al., 2006; Kneitel and Perrault, 2006), and human-mediated dispersal (Mack et al., 2000; Floerl and Inglis, 2005; Pysek et al., 2008) both of which should be high in the urban environment, so the presence and abundance of invasive species was investigated in relation to potential surro-

gates of disturbance; urban land use, distance from the city center, distance from nearest forest preserve, percentage of impervious surface, and median household income. Alternatively, one might expect that there are few opportunities for 'wild' plant species in the environments with high percentages of impervious surface, albeit highly disturbed.

Garlic mustard (*Alliaria petiolata*), a major invasive species of woodlands, was observed in residential areas and that stimulated our interest in this problem. The relationship between urban land use and other attributes of urban structure and invasive plant species presence and abundance seemed of interest to both urban planners and to land managers of urban natural areas. Eight ecologically problematic species were selected for study. Each was large and/or distinct enough to be effectively assayed by walking in the public spaces of urban areas. We confirmed the ecologically problematic status of the studied species by surveying local land managers. Urban ecological surveys are becoming more common, in part because urban areas are increasingly becoming habitat for wild animals (Blair and Launer, 1997; Morey et al., 2007; Sorace and Gustin, 2009; Vallejo et al., 2009). No one to our knowledge, however, has published a paper on a survey of ecologically problematic invasive plant species within an urban landscape.

Traditional metropolitan areas have anthropogenic activities and impact structured by distance from a center. As one moves away from the city center, the buildings change from predominantly expensive, tall, multiunit structures to shorter multiunit housing to dense single family residences to less dense residences with more lawns and gardens and then eventually to agricul-

\* Corresponding author. Tel.: +1 312 996 2643; fax: +1 312 996 2511.  
E-mail addresses: [pgulez2@uic.edu](mailto:pgulez2@uic.edu) (P.Z. Gulezian), [csnp@uic.edu](mailto:csnp@uic.edu) (D.W. Nyberg).

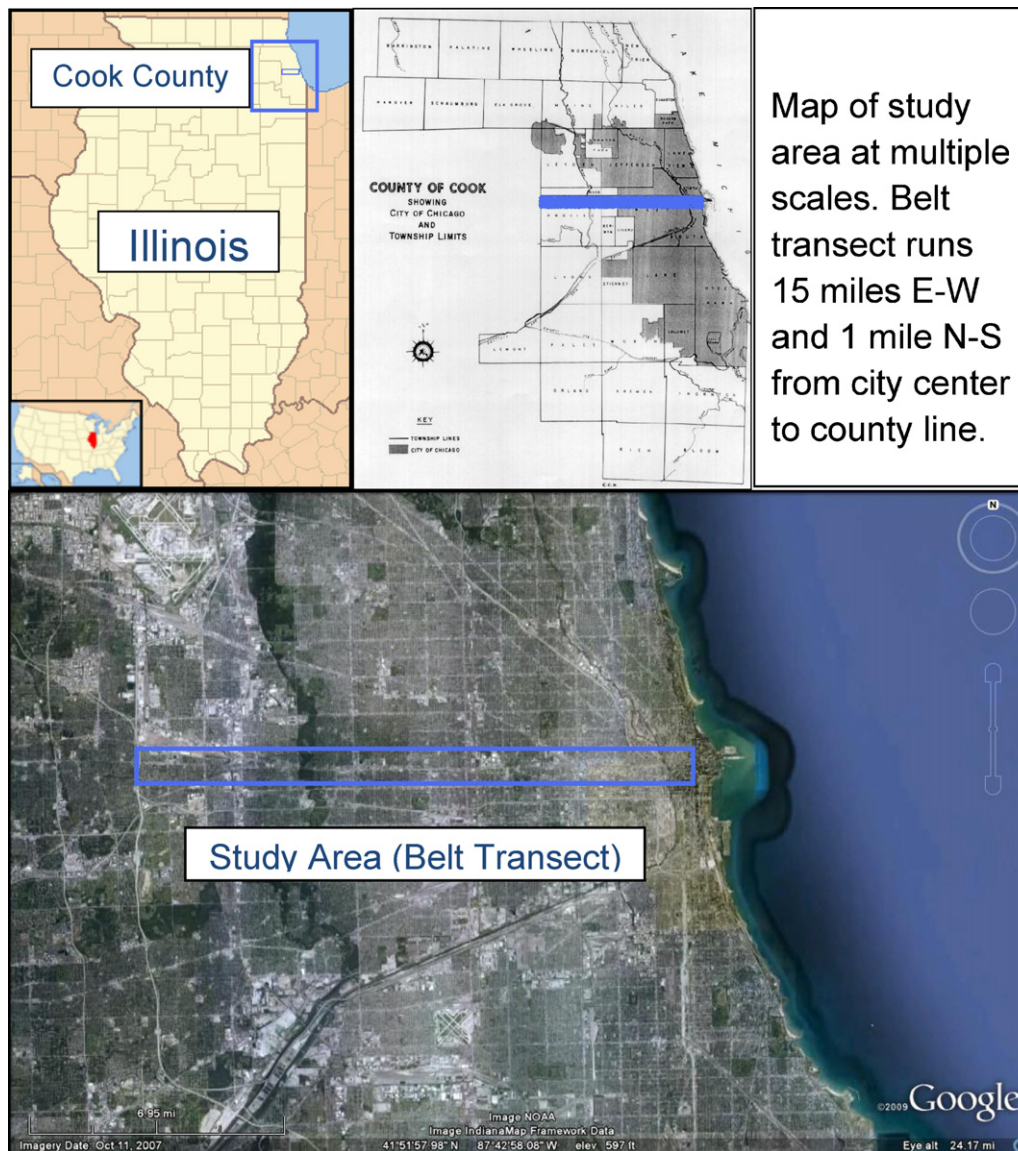


Fig. 1. Map of study area at multiple scales. Belt transect runs 15 miles E–W and 1 mile N–S from city center to county line.

tural land. In many metropolitan areas, Chicago included, there are zone(s) occupied by lower income individuals that includes vacant lots and buildings, separate municipal governments and areas set aside for nature that complicate the distance gradient. In Chicago, IL, USA the city center is close to Lake Michigan. A transect extending 15 miles (24 km) west of the city center to the county line generally conforms to the above pattern, but does not even approach agricultural land (Fig. 1). Little is known about patterns of species richness across such a gradient of urbanization (Puth and Burns, 2009). Our principal aim is to document and analyze patterns of abundance of ecologically problematic invasive plants across a gradient of spatial urban structure. Correlations of the urban variables with the abundance of invasive plants should identify if and how land use planning affects abundances of ecologically problematic species.

Urban environments offer advantages for plot sampling because roads provide pre-defined sampling units, i.e., the block. In places, including Chicago, where the roads follow a grid system, it is simple to get a random sample of equal area plots within a belt transect. Each block can be surveyed from the public space around and within the plot. Eighty (80) blocks were randomly selected within our 15-square mile (38.8 km<sup>2</sup>) belt transect. Within each sample block the abundance of 10 invasive plants and the percentage of res-

idential (houses, apartments and vacant separately), commercial (active and vacant separately), parks, railroad corridor and forest preserve land was measured.

The main hypotheses investigated were: (1) multiunit residences should decline with distance from the city center; (2) the percent cover of impervious surfaces (roofs and pavement) is also expected to decline with distance from the city center; (3) plant abundance should be negatively correlated with percent impervious surfaces; (4) land use categories will explain a significant portion of plant abundance variation; (5) abundances of some pairs of species will be positively correlated because of similar habitat needs and life history traits.

## 2. Methods

### 2.1. Species selection and attributes

The eight species initially chosen for inventory are considered to be problems in local conservation areas. They are also efficiently detectable by walking public spaces late in the growing season. Specifically, the species are tall (>1.4 m, see Table 1) and/or possess a distinctive leaf shape. Our eight 'focal' species

**Table 1**  
Inventoried invasive plant species and some life history characteristics.

Species	Common name	Life cycle	Adult height range (m)	Date of first Cook County collection	Habitat description from Swink and Wilhelm's <i>The Plants of the Chicago Region</i> (1994)	Percentage (%) of natural areas sites detected (N = 16)	Mean management problem rating rank
<i>Ailanthus altissima</i>	Tree-of-heaven	Perennial Tree	12–30	1905	Older residential and industrialized areas, usual habitat is in alleys, in narrow spaces between buildings	13	10
<i>Alliaria petiolata</i>	Garlic mustard	Biennial forb	0.75–1.5	1953	Disturbed shaded ground, disturbed wooded floodplains	94	2
<i>Arctium minus</i>	Common burdock	Biennial forb	1–2	1939	Disturbed floodplain woods, weed patches, dump heaps, places of high nitrogen soils	94	6.5
<i>Cirsium vulgare</i>	Bull thistle	Biennial forb	0.75–1.75	1939	Abandoned fields, overgrazed pastures	100	4
<i>Dipsacus silvestris</i>	Common teasel	Biennial forb	1–2.5	1952	Near cemeteries and greenhouses, old fields, waste ground	69	5
<i>Melilotus alba</i>	Sweet clover	Biennial forb	1.5–3.5	1877	Abandoned fields, waste ground, railroads, degraded prairie remnants	81	6.5
<i>Phragmites australis</i>	Common reed	Perennial grass	1.5–5	1887	Marshes, where river dredgings have been deposited, along ditches	69	9
<i>Rhamnus cathartica</i>	Common buckthorn	Perennial tree	2–8	1899	Invades gardens, fencerows, and pastures	100	1
<i>Rosa multiflora</i>	Multiflora rose	Perennial shrub	1.5–3.5	1976	Almost every degraded terrestrial habitat	94	3
<i>Setaria glauca</i>	Yellow foxtail	Annual grass	0.5–1	1977	Cultivated ground, abundant along highways	75	8

include one tree, common buckthorn (*Rhamnus cathartica*); a shrub, multiflora rose (*Rosa multiflora*); five biennial forbs, garlic mustard (*A. petiolata*), teasel (*Dipsacus silvestris*), common burdock (*Arctium minus*), sweet clover (*Melilotus alba*), and bull thistle (*Cirsium vulgare*); and a perennial wetland grass, common reed (*Phragmites australis*). Two species commonly observed during the inventory were added to the list, namely tree-of-heaven (*Ailanthus altissima*) and Yellow foxtail, an annual grass (*Setaria glauca*) bringing the total species studied to 10. All 10 are non-native species (Swink and Wilhelm, 1994). Table 1 summarizes relevant ecological information about this set of species. Swink and Wilhelm's *Plants of the Chicago Region* was also the source of information on the habitat preferences of these species. The information on each species' maximum adult height was found on the United States' Department of Agriculture (USDA) Plants Database (<http://plants.usda.gov/>). The earliest recorded date of a herbarium specimen known from Cook County was from an online database, vplants (<http://www.vplants.org/>). To corroborate that the species are problems for regional ecosystems, we asked natural area stewards on a listserve ([vs-stewards@yahoogroups.com](mailto:vs-stewards@yahoogroups.com)) to comment on each species' status in their preserves. Stewards were asked to put each species into 1 of 4 categories: 0 = not present; 1 = present but not a significant problem; 2 = a significant problem; 3 = a major problem (one of the worst three species in terms of their own on-site management effort). Using the average values from 16 sites sent by eleven stewards we ranked the 10 species, with the rank of 1 representing the greatest problem.

## 2.2. Transect and block selection

In Chicago, State St. is the zero line that separates east from west and Madison St. is the zero line that separates south from north. Our urban transect runs 24 km west of State St. to the Cook County boundary, with Madison St. as the south boundary and Chicago Ave. 1.61 km north as the north boundary. Within that belt transect, the

Chicago city limit is 12 km west and the forest preserves along the Des Plaines River are about 16 km west of State St. Fig. 1 shows the study area belt transect at multiple spatial scales.

Urban environments have been divided into blocks which make a 'natural' unit for ecological sampling. The edge of our plot is the center of the bordering streets, which clearly delineate the plot boundaries and have no plants growing near the edge. Standard blocks have an alleyway down the middle and are bounded by named streets on all four sides. In Chicago, roads and blocks were made using the rectangular cardinal direction lines of the Public Land Survey (early 19th century in Illinois). Since the land is flat, almost all blocks correspond to the standard of 1/16th by 1/8th mile (=2.0234 ha).

As the entire 38.85 km<sup>2</sup> sample belt was already divided into blocks, making the study plot a block simplified selecting a random sample of the area. The Chicago address numbering system was used to locate the blocks to be inventoried. Madison St. is 0N and Chicago Ave. is 800N, so the first digit in a four-digit random number set defined the north/south location of the block (only numbers beginning with 0–7 are used). The county line is 240 blocks west of State St. so the second through fourth digits in a set define the east/west location of the block (skipping numbers in the table >240). In the suburban areas west of the Des Plaines River, all streets did not run in the cardinal directions and features such as railroad corridors resulted in some blocks that were not the standard size. We continued to use a block bordered by streets as our sample unit and chose roads defining the borders to match the standard as closely as possible. For the analysis were treated each sample block as having an area of 2.0 ha. The 80 blocks studied were 4.2% of the total belt area.

## 2.3. Block attributes and species inventories

The distance from the nearest forest preserve was measured on the recreational facilities map of the Forest Preserve District

of Cook Co (FPDCC). All but 15 blocks were closest to the FPDCC preserve that was located within the belt transect. The proportion of the block covered by impervious surface was estimated using GoogleEarth ([www.google.com](http://www.google.com)) images. To associate a measure of wealth with each block we determined the zip code of each sampled block. For each zip code, the median household income in the 2000 US Census was accessed at the website of the Northeastern Illinois Planning Commission ([www.nipcc.org](http://www.nipcc.org)). The direct link to the census information can be found at <http://www.nipcc.org/census.2000.gate.htm>. All blocks with the same zip code had the same income value. Nine land use categories {1: houses and small flats (occupied) or 2: (vacant); 3: multiunit residences (occupied) or 4: (vacant); 5: commercial and industrial (active) or 6: (vacant); 7: parks; 8: railroad corridor; and 9: forest preserve land} were recorded in the field during the inventory. On each block percent usage was constrained to add to 100%. All vacant houses, apartments and commercial land were combined into a single 'vacant' category.

Each block was inventoried by walking all accessible areas (all streets, sidewalks, medians, alleyways, vacant lots, parking lots, and even between apartment buildings and on top of railroad embankments) and counting individuals of each of the 10 invasive species. Walking surveys were conducted in September and October of 2006, at the end of the growing season when the majority of our species were as tall as they would get. Only garlic mustard is clearly not near its optimal detection time at the end of the summer. Even so, first year garlic mustard plants are still green with distinctive leaves and odor, and second year plants, though having already senesced, are often still standing as tall, light brown stalks of distinctive appearance.

Five categories of abundance on the block were scored: 0 = not present; 1 = 1–4 detected; 2 = 5–99 detected; 3 = 100–1000 detected; 4 = >1000 individuals detected. Once more than five individuals were counted, the total number was estimated as more than 100 or 1000. To convert the abundance categories into population estimates the following numbers were used: category 1 = 3 individuals; category 2 = 30 individuals; category 3 = 300 individuals; and category 4 = 3000 individuals; which are close to the midpoints (3.16) of each category on a log scale.

2.4. Quantitative and statistical analysis

Means, counts, and ordered sorting was done with a spreadsheet. For all variables the lowest value was given the rank of 1 (if there was a single instance of that value) and large values had higher ranks. Spearman correlation of the ranks was the method evaluating the relationships of pairs of variables. Positive correlations implying low values of one variable are associated with low values of the other variable. The sample block that fell in the forest preserve was exceptional on the basis of its land use and percentage of impervious surface, so we decided to exclude it from the corre-

lation analysis. Because of many tied ranks, correlations of the land use variables parks and railroad corridor, and the abundances of teasel, common reed and multiflora rose are not reported.

Correlation of ranks was calculated using the Spearman correlation coefficient, or rho, as recommended by Zar (1996). The variables paired were distance to city center (State St.), distance to the closest forest preserve, median household income, percentage impervious surface, percentage in land use categories (active houses, active apartments, active commercial/industrial and vacant), abundance for the seven invasive species with over three occurrences, total number of invasive species present on the block, and the sum of the abundance categories of all invasive species. With 136 correlated pairs the Bonferroni corrected value to be considered significant at the  $\alpha = 0.05$  level using two-tailed test is  $r > 0.40$  for  $\nu = 77$  (interpolated from Zar, 1996).

The expected distribution of the total number of invasive species on each block was calculated using the Poisson distribution and the observed and expected numbers were evaluated for randomness (Zar, 1996). Presence-absence associations of species pairs were evaluated with Fisher's exact test (Zar, 1996). Graphical presentation of relationships with distance from city center in Fig. 4 used a five-block window to produce a smoothed curve.

3. Results

3.1. Urban transect characterization

Table 2 shows how many blocks fell into five percentage categories for each land use (part a) and impervious surfaces (part b). If one labels blocks with >75% in a land use category 'pure' and the others as 'heterogeneous,' then almost half of the blocks (37 of 80) are heterogeneous in land use. Of the 43 pure blocks, six are parks and one is the forest preserve sample block, so 36 of those with buildings are pure. Both the highest total percentage and the highest number of pure blocks' land use are single family residences (Table 2). The entire inventoried land area contains a little more than 75% impervious surfaces, leaving about a quarter of the total area to be potentially colonized by invasive plants. Two thirds of the blocks (54/80) had less than a quarter of their area as exposed soil, i.e., were 'pure' impervious, but some plants do grow in cracks in impervious surfaces.

3.2. Presence-absence on blocks

Nine of the ten invasive species were found in at least one of the 80 sample blocks and three species were found in 50% or more blocks. In Fig. 2 the species are ordered by frequency of occurrence. The mean number of invasive species present on a block was 2.74. When that mean is used for  $\lambda$  in the Poisson distribution, the expected number of blocks with 0, 1, 2, 3, 4 and >4 species is illustrated in Fig. 3 along with the observed numbers in each cat-

**Table 2**  
 Number of 80 blocks falling into percentage categories for (a) land use types and (b) percent of area occupied by impervious surfaces.

	Percent use category					Total all 80 blocks
	0%	1–25%	26–50%	51–75%	76–100%	
<b>(a) Land use</b>						
Houses	30	9	13	8	20	39.5%
Multiunit	60	6	11	2	1	9.9%
Commercial	34	23	7	3	13	25.4%
Vacant	41	27	5	5	2	12.3%
Parks	69	4	1	0	6	8.4%
RR	64	14	2	0	0	3.3%
FPD	79	0	0	0	1	1.2%
<b>(b) Percentage impervious</b>						
Impervious	1	4	3	18	54	75.9%

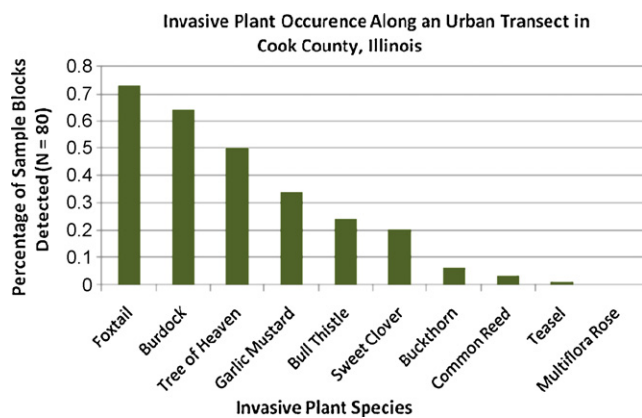


Fig. 2. Invasive plant species detected by sample block along an urban transect in Cook County, IL.

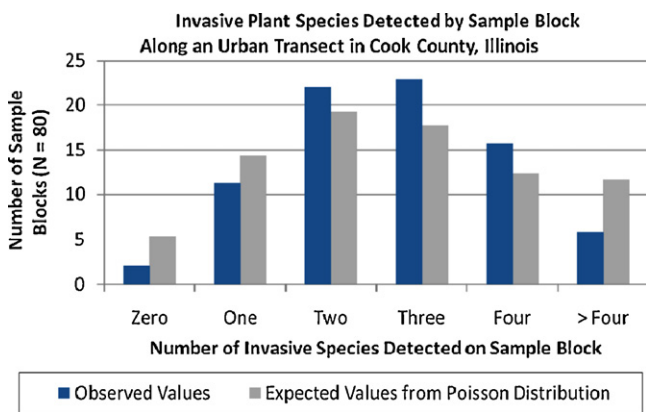


Fig. 3. Median household income (by zipcode, N = 17) and mean invasive plant presence along the urban gradient in Cook County, IL.

egory. The observed numbers of blocks are compatible with the null hypothesis that all blocks are equally likely to receive any species ( $Pr = 0.14$ ,  $\chi^2 = 8.3$ ,  $df = 5$ ). If the blocks were heterogeneous, with some especially resistant to and others especially receptive to these invasive species, one would expect the observed number to exceed the expected in the two most extreme categories (zero species per block and >4 species per block), but those categories have less observations than expected from the Poisson, corroborating the implication that all blocks are equally likely to contain invasive plant species.

### 3.3. Abundance of invasive species in urban areas

Table 3 shows number of blocks in each abundance category for the 79 blocks in the built urban environment and gives estimates for the total number of individuals detected of each species and

Table 3

Abundance of invasive species in the built urban environment. Frequencies of blocks (N = 79) in abundance categories for each species and estimates of average abundance per urban hectare.

Abundance category	Focal invasive species							Additional invasive species	
	Garlic mustard	Burdock	Sweet clover	Thistle	Common reed	Teasel	Buckthorn	Foxtail grass	Tree-of-heaven
0	53	28	63	60	77	78	75	23	40
1	5	7	5	6	0	0	2	3	16
2	11	32	8	10	1	0	2	31	22
3	6	10	1	2	0	0	0	16	1
4	4	2	2	1	1	1	0	6	0
Total detected	14,145	9981	6555	3918	3030	3000	66	23,739	1008
Density per hectare	88.5	62.4	41.0	24.5	19.0	18.8	0.4	148.5	6.3

the density per urban hectare. The single forest preserve sample block had over 1000 garlic mustard individuals, over 100 buckthorn (the only sampled block above 100), between 5–99 foxtail and tree-of-heaven, and 1–4 burdock. Each of the seven herbaceous species had at least one block with over 1000 individuals present. The two trees (buckthorn and tree-of-heaven) and woody shrub (multiflora rose) had low abundance rankings compared to their frequency ranking at least in part because trees have a considerably greater maximum size and correspondingly lower abundances. When summed, the average density estimate for all 10 invasive species was 425 individuals per hectare. The average density estimate for our eight ecologically problematic species was 271 individuals per urban hectare. This average is less than the minimum estimate of 600 ha<sup>-1</sup> and the estimate of 1800 ha<sup>-1</sup> using the standard category abundance estimates for our single forest preserve block and considerably lower than our impression of their abundance in natural areas. The averages calculated include all the zeros from where the species was not present and since much of the urban area (75%) had impervious surfaces, it is difficult to compare urban and natural areas fairly.

### 3.4. Urban spatial patterning by distance and land use

Correlations of the ranks were used to evaluate relationships of distance and land use in upper left part of Table 4 (through vacant). Correlations with an absolute value >0.40 (in bold) are considered statistically significant ( $p < 0.05$ ), but the high correlation, -0.75, of distance to city center and distance to nearest forest preserve was essentially determined in the selection of the transect. The high negative correlation, -0.63, of houses and commercial/industrial is partially a constraint that percentage land use must sum to 100%, and houses and commercial/industrial were the two highest land uses (Table 2).

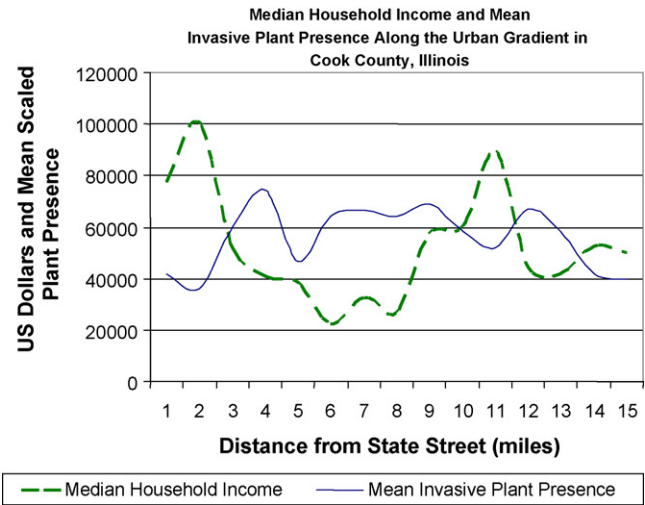
The statistically significant correlations among urban attributes are as follows: percentage of houses increases as distance to city center increases (0.43), as distance to forest preserves gets smaller (-0.47), and as vacancy declines (-0.43); the percentage of land in apartments was not significantly related to any other variable, even though we expected a negative correlation to the distance to city center. Commercial/industrial percentage increased as distance to nearest forest preserve increased (0.43) and was also associated with a higher percentage of impervious surfaces (0.45). Vacancy increases as household incomes decline (-0.46). Also notable were the findings that income, percentage impervious, and the land use categories (except houses) were not significantly correlated with distance to the city center within the studied belt transect.

Correlations among the urban variables and the abundances of invasive species were generally not significant. Only three significant correlations were found. The abundance of burdock declines as income increases (-0.47) and as percentage commercial/industrial declines (-0.46). The total abundance of invasive species increases as percentage impervious declines (-0.41). Only one of the remain-

**Table 4**  
Correlations of the ranks of block attributes—spatial, income, land use and common invasive species abundance of the 79 built-upon blocks.

Attribute	Dist city center	Dist FPreserve	\$\$\$\$	Impervious	House	Apartment	Com & Ind	Vacant	Garlic mustard	Burdock	Sweet clover	Thistle	Buckthorn	Fox tail	Tree of heaven	Presence	Abundance
Dist city center	1.00																
Dist FPreserve	<b>-0.75</b>	1.00															
Income	0.33	-0.30	1.00														
Impervious	-0.07	0.11	0.24	1.00													
House	<b>0.43</b>	<b>-0.47</b>	0.20	-0.04	1.00												
Apartment	-0.11	0.02	-0.13	0.07	0.04	1.00											
Com & Ind	-0.30	0.43	0.10	<b>0.45</b>	-0.63	-0.15	1.00										
Vacant	-0.29	0.23	<b>-0.46</b>	-0.29	<b>-0.43</b>	-0.15	0.23	1.00									
Garlic mustard	0.08	-0.18	-0.01	-0.14	0.07	0.20	-0.14	0.01	1.00								
Burdock	-0.05	-0.06	<b>-0.47</b>	-0.26	0.26	0.05	<b>-0.46</b>	0.21	0.20	1.00							
Sweet clover	-0.23	0.17	-0.02	-0.21	-0.23	0.05	0.06	0.35	-0.08	0.08	1.00						
Thistle	-0.18	0.06	-0.23	-0.20	-0.17	-0.20	-0.08	0.20	-0.12	0.20	-0.07	1.00					
Buckthorn	0.17	-0.27	0.06	-0.18	-0.01	-0.13	-0.10	0.07	0.14	0.08	0.15	-0.02	1.00				
Fox tail	-0.02	-0.09	0.01	-0.18	0.04	0.07	-0.15	0.15	0.01	0.01	0.17	0.10	0.07	1.00			
Tree-of-heaven	0.06	-0.14	-0.23	0.06	0.26	0.20	-0.07	0.22	0.11	<b>0.44</b>	-0.02	0.03	-0.08	0.02	1.00		
Presence	0.01	-0.20	-0.23	-0.39	0.17	0.18	-0.33	0.30	0.43	<b>0.62</b>	0.33	0.28	0.21	<b>0.43</b>	<b>0.53</b>	1.00	
Abundance	-0.09	-0.07	-0.36	<b>-0.41</b>	-0.01	0.11	-0.27	<b>0.45</b>	0.41	<b>0.60</b>	0.38	0.36	0.15	0.52	<b>0.44</b>	<b>0.91</b>	1.00

For all variables low values were given low ranks. Correlations with an absolute value >0.40 (in bold) are significant at the 5% level (with 77 degrees of freedom, Bonferroni corrected for 136 paired comparisons, two-tailed test, interpolated from Zar, 1996).



**Fig. 4.** Invasive plant occurrence along an urban transect in Cook County, IL.

ing 53 pairs has a correlation with absolute value greater than 0.3 (sweet clover, vacant), so  $R^2$  is less than 10% for 52 of 56 urban/invasive variable pairs.

Correlations of abundances between invasive species were low. Tree-of-heaven abundance increases significantly as burdock abundance increases (0.44), but the next highest correlation among the 21 species pairs is 0.20 which explains less than 4% of the variation. The collective presence and abundance of all 10 invasive species tended to a negative relationship with income and impervious percentage and a positive relationship with percentage vacant. The collective presence or abundance was not related to distance from the city center.

Correlations are effective at detecting linear relationships between variables, but there may be strong relationships that are non-linear. Fig. 4 illustrates the spatial relationship of both total invasive species presence and income versus distance from the city center (neither of which had a statistically significant linear correlation). The lowest average presence of these 10 species occurs closest to downtown, where residents are wealthiest and available habitat (exposed soil) is rarest. Invasive presence rises just west of the wealthy downtown neighborhoods where households are poorer and available habitat increases (vacant lots, for example), and stays relatively high until the second peak in median household income, which occurs in the wealthy suburbs of Oak Park and River Forest, which have very little vacant land, but large lawns and gardens. Just west of the wealthiest suburbs in the transect, the invasive presence rises again to levels on par with those of the poorer city neighborhoods, then falls to very low levels at the end of the transect.

### 3.5. Invasive species in urban and natural areas

Eleven stewards responded to our query and provided information on all 10 species in 16 managed natural areas, 12 of which were in Cook County. The stewarded sites ranged from 0.4 to 200 ha, and include prairies and woodlands. Nine of our ten inventoried invasive species were present on more than 10 of the 16 sites. Only tree-of-heaven was absent from the majority of these natural areas. Bull thistle and common buckthorn were reported from all 16 natural areas (Table 1). Based on the numerical ratings reflecting management problems provided by stewards (max 3, min 0) the greatest management problems were caused by buckthorn (2.5), followed by garlic mustard (2.0), multiflora rose (1.7), bull thistle (1.6), teasel (1.2), burdock (1.1), sweet clover (1.1), foxtail (0.8), reed (0.7) and tree-of-heaven (0.1). The Spearman rank correlation

of the management problem ranking with rank of urban abundance is  $-0.20$  and with urban frequency is  $-0.37$ . While neither correlation is significantly different than zero, the negative values suggest these species do not respond to urban and natural areas as equivalent habitats. While garlic mustard, teasel and sweet cover have similar ranks in both environments, foxtail, tree-of-heaven and burdock seem to be more urban species, while multiflora rose and buckthorn are species more connected to natural areas.

#### 4. Discussion

It seems obvious that at some scale all urban areas have a 'center' and are spatially structured by distance, but the regularity of distance structure is not uniform, probably because corridors of transportation override a simple diffusion model. The transect studied is entirely within the urban area, includes a major railroad line and is parallel to an interstate highway. Within that transect neither the main hypothesis that the proportion of multiunit residences would decline with distance nor the hypothesis that proportion impervious would decline with distance was supported by the random sample of blocks. The statistically significant structure that we did find was that the proportion of houses increased with distance from the city center. Given the weak relationships of urban variables with distance, land use or other urban variables seem to have more potential to interpret the abundances of animals (Blair and Launer, 1997; Dunning et al., 1992) and plants (Crowe, 1979) in the urban environment.

Only one invasive species registered a statistically significant correlation to any land use variable (Table 4), namely burdock. Burdock abundance was negatively correlated with the proportion of commercial/industrial land. Burdock was also negatively correlated with income, perhaps due to the undesirable Velcro-like hooks of its seeds. Residents in wealthier neighborhoods may have the resources to remove burdock plants more diligently. In urban areas burdock may be spread primarily by pets and larger urban mammals such as opossums (*Didelphis virginiana*) and raccoons (*Procyon lotor*). The invasive species that was not found in the urban area was multiflora rose, a species known for its annoying thorns. Collectively, the total abundance of all 10 species increased as the percentage of impervious surface decreased, supporting our third hypothesis, but this happened rather weakly as no individual species' abundance was significantly correlated to percentage of impervious surface. Total abundance had a suggestive negative relationship to household income (see Fig. 3). Income does not have a simple relationship to land use. Individuals with high incomes can afford residences in many neighborhoods, and some prefer the downtown area while others prefer well-tended lawns and gardens with contractual landscaping. Our income values were based on zip code and possibly a higher resolution association of income with sample blocks would be informative. High income areas do have low levels of vacancy. Vacant areas provide opportunities for plants to reproduce and increase in abundance (Baker, 1974; Crowe, 1979). Indeed, in a study of the weeds of vacant lots in Chicago's Hyde Park neighborhood, Crowe (1979) found that vacant lots that were older, larger, and unmowed had significantly higher levels of species richness (most of which were non-native plants) than younger, smaller, and mowed lots (Crowe, 1979). Thus, more available habitat and lower levels of eradication (weeding, mowing, herbiciding, etc.) are likely to account for the negative correlation between overall invasive plant presence and mean local income level. Income seems to have more potential to explain abundance of invasive species in the urban environment than land use, at least for the land use categories that we used.

Pairs of species are expected to have a positive association of presence if they have similar ecological needs, but might show negative relationships of abundance if they were competitors.

Since similar species often coexist by exploiting different facets of a landscape's geography (MacArthur, 1972), physical structure (MacArthur, 1958) and the resources connected to that structure (Tilman, 2004) positive associations in space were expected. Specifically, it seemed likely that biennial species would have positive abundance correlations. In our data no pairs were negatively correlated and the sole pair with positively correlated abundances, burdock and tree-of-heaven, are more or less opposites in terms of life cycles and other attributes. This association was also identified applying Fisher's exact test to presence-absence data. Though both the urban environment and the attributes of the invasive species studied seem very heterogeneous, our hypothesis (fifth) of associations between species was not supported. Evidence from our study suggests that, except for one difficult to rationalize pair, each of the 10 invasive species view the urban habitat as independently homogeneous.

While this suite of plants may not respond to the human-appraised habitat variation within the urban environment, some evidence suggests the species differentiate between the urban environment and natural areas. Rank correlation between urban abundance level and the problem rating by natural areas stewards is negative. The three most frequent species in the urban environment include our two added species (foxtail and tree-of-heaven) that are among the bottom three on the problem ranking by the stewards. Those two species and burdock are more connected to urban land. Buckthorn is most connected to natural areas. Only garlic mustard has a high presence and abundance in both urban and natural environments.

How do these species enter the urban environment? There is probably some planting of both tree species, but we doubt urban residents are deliberately planting any of the other eight. As weeds the species probably have high rates of colonization and extirpation (Crowe, 1979). In such situations one tries to identify sources and sinks (Dunning et al., 1992; Dias, 1996; With, 2002). We suspect that the built-upon urban environment may be a sink rather than a source for the majority of our species. Evidence that leads to that opinion is the lack of a positive relationship between urban abundance and the problem rating, the tendency for garlic mustard ( $r = -0.18$ ) and buckthorn ( $-0.27$ ) to be more abundant closer to forest preserves, and the high abundance of these species in the sample block that fell within the forest preserve. In the urban-area-as-a-sink idea, the built-upon urban environment receives more propagules from the preferred habitat of the invasive species (conservation areas) than the urban area contributes to that habitat. The distributions of these invasive species may be better explained by dispersion models (Crowe, 1979; Floerl and Inglis, 2005; Drake and Lodge, 2006) where the proximity to large source populations in forest preserve land explains some of the distribution across the urban gradient.

Pysek et al. (2008) found that there are two major mechanisms of spread of invasive plants—human influences and natural spread—and that the relative influence of the different mechanisms changes in an inverse proportion from the largest to the smallest spatial scale (continental, regional, local). It is clear that the spatial scale of the analysis partially determines the key results of any study of invasive plant spatial distribution (Levin, 1992), and in our case, it appears that human influences are not driving invasive plant spread in any clear way at a local scale. This potentially supports Pysek's finding that human influences were least influential at local scales (Pysek et al., 2008). It should be noted, however, that distinguishing between observed patterns and the processes responsible for them has been difficult in ecology, especially in invasion biology (Fridley et al., 2007; Herron et al., 2007). In our study, many commonly used land use variables do not explain in any strongly predictive way the presence or abundance of invasive plant species, either individually or collectively, in the urban landscape.

## 5. Conclusions

The distributions of invasive plants in urban areas are relatively unknown to both ecologists and urban planners. This study provides evidence that most ecologically problematic invasive plants are present on blocks sampled in a belt transect in Chicago, IL. Collectively, abundance was negatively related to percent impervious surface, and presence was negatively related to local income. No invasive species' abundance was structured by distance and only one of 10 species, burdock, had any significant correlations with land use. This general lack of connection to land use is unexpected, and suggests most plant species find opportunities independent of land use at the scale of our analysis. Urban planners who wish to incorporate ecological principles and values into their work will not find much guidance from our study, but they may find solace. The species locally regarded as the biggest problems in natural areas are rarely among the most common in the city and abundances suggest urban areas do not serve as sources of ecologically problematic invasive plant species, but rather are more likely sinks, receiving more propagules from the forest preserves than are sent into natural areas of conservation concern.

## Acknowledgements

This work was supported by the National Science Foundation's Integrative Graduate Education and Research Traineeship (IGERT) grant program. The IGERT program concerning Urban Ecology at the University of Illinois at Chicago is titled: Landscape, Ecological, and Anthropogenic Processes (LEAP), and can be found at <http://www.uic.edu/depts/bios/leap>.

## References

- Anderson, R.C., Dhillon, S.S., Kelley, T.M., 1996. Aspects of the ecology of garlic mustard (*Alliaria petiolata*) in central Illinois. *Restor. Ecol.* 4, 81–91.
- Baker, H.G., 1974. The evolution of weeds. *Annu. Rev. Ecol. Syst.* 5, 1–24.
- Blair, R.B., Launer, A.C., 1997. Butterfly diversity and human land use: species assemblages along an urban gradient. *Biol. Conserv.* 80, 113–125.
- Chittka, I., Schurkens, S., 2001. Successful invasion of a floral market. *Nature* 411, 653.
- Coblentz, B.E., 1990. Exotic organisms: a dilemma for conservation biology. *Conserv. Biol.* 4, 261–265.
- Crowe, T.M., 1979. Lots of weeds: insular phytogeography of vacant urban lots. *J. Biogeogr.* 6, 169–181.
- Dias, P.C., 1996. Sources and sinks in population biology. *Trends Ecol. Evol.* 11, 326–330.
- Drake, J.M., Lodge, D.M., 2006. Alle effects, propagule pressure and the probability of establishment: risk analysis for biological invasions. *Biol. Invasions* 8, 365–375.
- Duda, J.J., Freeman, D.C., Emlen, J.M., Belnap, J., Kitchen, S.G., Zak, J.C., et al., 2003. Differences in native soil ecology associated with invasion of the exotic annual chenopod, *Halogeton glomeratus*. *Biol. Fertil. Soils* 38, 72–77.
- Dunning, J.B., Danielson, B.J., Pulliam, H.R., 1992. Ecological processes that affect populations in complex landscapes. *Oikos* 65, 169–175.
- Floerl, O., Inglis, G.J., 2005. Starting the invasion pathway: the interaction between source populations and human transport vectors. *Biol. Invasions* 7, 589.
- Fridley, J.D., Stachowicz, J.J., Naeem, S., Sax, D.F., Seabloom, E.W., Smith, M.D., et al., 2007. The invasion paradox: reconciling pattern and process in species invasions. *Ecology* 88, 3–17.
- Heger, T., Trepl, L., 2003. Predicting biological invasions. *Biol. Invasions* 5, 313–321.
- Herron, P.M., Martine, C.T., Latimer, A.M., Leicht-Young, S.A., 2007. Invasive plants and their ecological strategies: prediction and explanation of woody plant invasion in New England. *Divers. Distrib.* 13, 633–644.
- Hierro, J.L., Villarreal, D., Eren, O., Graham, J.M., Callaway, R.M., 2006. Disturbance facilitates invasion: the effects are stronger abroad than at home. *Am. Nat.* 168, 144–156.
- Huxel, G.R., 1999. Rapid displacement of native species by invasive species: effects of hybridization. *Biol. Conserv.* 89, 143–152.
- Kneitel, J.M., Perrault, D., 2006. Disturbance-induced changes in community composition increase species invasion success. *Community Ecol.* 7, 245–252.
- Levin, S.A., 1992. The problem of pattern and scale in ecology. *Ecology* 73, 1943–1967.
- Levine, J.M., Vila, M., D'Antonio, C.M., Dukes, J., Grigulis, K., Lavorel, S., 2003. Mechanisms underlying the impacts of exotic plant invasions. *Proc. Roy. Soc. Lond.* 270, 775–781.
- MacArthur, R.H., 1958. Population ecology of some warblers of northeastern coniferous forests. *Ecology* 39, 599–619.
- MacArthur, R.H., 1972. *Geographical Ecology: Patterns in the Distribution of Species*. Harper and Row, New York.
- Mack, R.N., Simberloff, D., Lonsdale, W.M., Evans, H., Clout, M., Bazzaz, F.A., 2000. Biotic invasions: causes, epidemiology, global consequences, and control. *Ecol. Appl.* 10, 689–710.
- Morey, P.S., Gese, E.M., Gehrt, S., 2007. Spatial and temporal variation in the diet of coyotes in the Chicago metropolitan area. *Am. Midl. Nat.* 158, 147–161.
- Pimentel, D., Zuniga, R., Morrison, D., 2005. Update on the environmental and economic costs associated with alien-invasive species in the United States. *Ecol. Econ.* 52, 273–288.
- Puth, L.M., Burns, C.E., 2009. New York's nature: a review of the status and trends in species richness across the metropolitan region. *Divers. Distrib.* 15, 12–21.
- Pysek, P., Jarosik, V., Mullerova, J., Pergl, J., Wild, J., 2008. Comparing the rate of invasion by *Heracleum mantegazzianum* at continental, regional, and local scales. *Divers. Distrib.* 14, 355–363.
- Rejmanek, M., Richardson, D.M., 1996. What attributes make some plant species more invasive? *Ecology* 77, 1655–1661.
- Sakai, A.K., Allendorf, F.W., Holt, J.S., Lodge, D.M., Molofsky, J., With, K.A., et al., 2001. The population biology of invasive species. *Annu. Rev. Ecol. Syst.* 32, 305–332.
- Sanderson, E.W., Jaiteh, J., Levy, M.A., Redford, K.H., Wannebo, A.V., Woolmer, G., 2002. The human footprint and the last of the wild. *Bioscience* 52, 891–904.
- Schmitz, D.C., Brown, T.C., 1994. An assessment of invasive non-indigenous species in Florida's public lands. Bureau of Aquatic Plant Management, FL Dept. of Environmental Planning. Technical Report No. TSS-94-100.
- Sorace, A., Gustin, M., 2009. Distribution of generalist and specialist predators along urban gradients. *J. Landscape Urban Plan.* 90, 111–118.
- Swink, F., Wilhelm, G., 1994. *Plants of the Chicago Region*, 4th ed. Indiana Academy of Science, Indianapolis.
- Tilman, D., 2004. Niche tradeoffs, neutrality, and community structure: a stochastic theory of resource competition, invasion, and community assembly. *Proc. Natl. Acad. Sci. U.S.A.* 101, 10854–10861.
- Vallejo Jr., B.M., Aloy, A.B., Ong, P.S., 2009. The distribution, abundance and diversity of birds in Manila's last greenspaces. *J. Landscape Urban Plan.* 89, 75–85.
- With, K., 2002. The landscape ecology of invasive spread. *Conserv. Biol.* 16, 1192–1203.
- Zar, J.H., 1996. *Biostatistical Analysis*, 3rd ed. Prentice Hall, Upper Saddle River, NJ.