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ORIGINAL PAPER

Decline in the diversity of willow trunk-dwelling weevils (Coleoptera: Curculionoidea) as a result of urban expansion in Beijing, China

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Abstract Beijing, the capital and second largest city of China, expanded in a typical concentric pattern. The urbanized area consists of five concentric zones, which are based on the city's ring road system. Willow trees (*Salix* spp.) are commonly planted and abundant in the city. In this study, we determined the effects of urbanization on willow trunk-dwelling weevils (Coleoptera: Curculionoidea) in a 3-year survey. Our results indicated that species richness and abundance decreased from outskirts to the urban center. It was estimated that within a 30-km limit, species richness and abundance might be reduced by 0.9 species and 59.3% of individuals per 5 km toward urban center. Landscape variables (e.g., the proportion of impervious surface and distance to urban center) explained 59.4% of species richness and 43.9% of species abundance. Local variables (e.g., plant resources and site size) explained only 4.9% of species richness and 4.7% of species abundance. Our results show that there is a negative relationship between urban expansion and weevil diversity. There are several ways in which such detrimental effects on biodiversity could be mitigated: (1) Optimization of urban landscape structures, as well as vegetation planting; (2) increasing connectivity between urban remnants and natural landscapes in the outskirts of the city; and (3) limiting the proportion of impervious surface in inner urban zones.

Keywords Biodiversity · Urbanization · Fragmentation · Impervious surface · Isolation · Partial least squares regression

Introduction

Urban development results in dramatic land transformations and profound changes to ecosystems, and is one of the most significant factors in the loss of native biodiversity (Czech et al. 2000; Czech 2004). Given that the global urban population is projected to double from 3.2 billion in 2005 to 6.4 in 2050 (United Nations Population Division 2008), urban expansion will undoubtedly continue into the foreseeable future. It is important to investigate the relationships between urban expansion and biodiversity to develop strategies to mitigate the potential detrimental impacts of urbanization on native wildlife.

The urban–rural gradient approach (McDonnell et al. 1997) has been used widely in studies on the ecological consequences of urbanization (McDonnell and Hahs 2008). Study sites are generally classified into three categories according to the proportion of impervious surface (PIS):

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urban (PIS > 50%), suburban (20% < PIS < 50%) and rural (PIS < 20%) (McKinney 2002). This approach has increased our understanding of the distribution of urban wildlife and the ecological processes associated with urbanization (McDonnell and Hahs 2008). Adding more gradients between urban and suburban (or rural) may increase our understanding of the responses of urban wildlife to such processes.

Urban green areas are important for insect conservation (Koh and Sodhi 2004; McFrederick and LeBuhn 2006; McGeoch and Chown 1997; McKinney 2002; Niemelä 1999). Studies on the responses of various groups of insects to urbanization have suggested that local variables (e.g., resource availability, patch size) and landscape factors (e.g., amount of urban matrix, isolation from natural landscapes) are important determinants of insect diversity in urban green areas (Ahrné et al. 2009; Koh and Sodhi 2004; Sadler et al. 2006; Wood and Pullin 2002). Local and landscape features are interdependent because urbanization commonly results in habitat loss, fragmentation, isolation and resource removal as the urban matrix expands (Rebele 1994). Separating the effects of these factors may identify ways of mitigating the negative impacts of urbanization on biodiversity. To achieve this, it is essential to select an appropriate focal species for detailed study (e.g., those that depend on resources that are not associated with urbanization on a local scale).

Studies on the effects of urbanization on native arthropod diversity have focused on flower visitors, foliage feeders, and understory dwellers, referring to many diverse taxa and guilds, such as butterflies (Blair and Launer 1997; Koh and Sodhi 2004; Li et al. 2009; Mauro et al. 2007), bumble bees (Ahrné et al. 2009; Kleijn and van Langevelde 2006; McFrederick and LeBuhn 2006) and bees (Hostetler and McIntyre 2001; Zanette et al. 2005) that visit flowers in urban gardens and forests, leaf-mining moths and gall-inhabiting moths on tree canopies (McGeoch and Chown 1997; Rickman and Connor 2003), insect communities on mugwort plots (Denys and Schmidt 1998), arthropod assemblages on creosote bushes (Rango 2005), and carabids (Alaruikka et al. 2002; Hartley et al. 2007; Magura et al. 2004, 2008; Niemelä et al. 2000, 2002, 2007), isopods (Hornung et al. 2007) and spiders (Shochat et al. 2004) that dwell on the ground. Various patterns of responses of different taxa and guilds to urbanization have been reported. Studies on more taxa and/or guilds may give us a more comprehensive understanding of the responses of biodiversity to urbanization. Weevils are a taxon of particular interest, as they are the largest group of beetles, and beetles as a group are the most diverse of all animal groups (New 2007). Similarly, insects that inhabit tree trunks are an interesting guild, as trunks link the canopy to the undergrowth.

Tree trunks are an integral part of the habitat of many species of insects. As well as inhabiting the trunk, insects use trunks as travel routes and resting places (Hanula and Franzreb 1998; Moeed and Meads 1983), and/or as a focus for locating mates (Majer et al. 2003). Tree trunks may be exposed to different types and degrees of human disturbance compared with the canopy and undergrowth communities. For example, tree trunks are exposed directly to air pollution, whereas the canopy may be pruned for ornamental or practical reasons, or exposed to pesticides. The undergrowth is exposed to trampling, and is often intensively managed for improving the soil conditions. Tree trunks represent a unique biotic and abiotic environment (Roland 2004), thus quantifying spatial patterns of trunk dwellers and identifying the factors that determine their distribution along an urban-rural gradient is an effective and important means to understand the effects of urbanization on native biodiversity.

In this 3-year study, we chose willow-associated weevils (Coleoptera: Curculionoidea) as focal organisms, because the changes in richness and composition of local weevil assemblages could provide meaningful information to better understand changes in their living conditions (New 2007). In addition, these weevils are easily captured, and therefore, are easily studied.

The aims of this study were as follows: (1) To determine the spatial pattern of weevil distribution along an increasing urbanization gradient; (2) to identify the factors that are important in maintaining weevil biodiversity in an urban landscape; (3) to separate the effects of landscape metrics from site-specific metrics such as resource availability and site size; (4) to compare the patterns of change of trunk-dwelling communities with those of upper-layer and under-layer communities provided by previous studies; and (5) to explore the relationships between urban expansion and insect diversity.

Methods

Study sites

Beijing (39°28′–41°05′ N, 115°20′–117°30′ E) is the capital and second largest city of China, with 14.39 million urban inhabitants in 2008 (National Bureau of Statistics of China 2009). During its urbanization, Beijing has developed in a unique "pancake-shaped" pattern (Wang et al. 2007). That is, there is a series of concentric ring roads within the city, which approximately demarcate areas of decreasing urbanization from the city center outwards (Liu et al. 2002; Ouyang et al. 2007). Based on this ring-road transportation system and the spatial pattern of the proportion of impervious surface (PIS) (Table 1; Ouyang et al.

2007), we divided the urban area of Beijing into five urban zones (UZs): UZ1 (within the 2nd ring road), UZ2 (between the 2nd and 3rd ring road), UZ3 (between the 3rd and 4th ring road), UZ4 (between the 4th and 5th ring road) and UZ5 (between the 5th and 6th ring road) (Table 1; Fig. 1).

In total, we investigated 25 sites spanning approximately 30 km along the northwest of Beijing (39°52′24″–40°5′58″N, 116°10′41″–116°29′5″E), 20 sites in 2007, 15 sites in 2008, and 17 sites in 2009. Among these sites, 11 were investigated every year, and 5 were investigated in 2 of the 3 years (Fig. 1). The sites included 12 urban parks and 13 green belts. To minimize the potential confounding effects from the age of surveyed trees, all selected sites contained at least 50 individuals of willows with a 10–20 cm diameter at breast height. All sites were less than 60 years old, except for the site at the Summer Palace (SP) and the site at the Old Summer Palace (OSP), both of which are more than 250 years old. The choice of sites was limited by availability in some zones, resulting in the variation of site size (ranging from 1.2 to 350 ha), and uneven distribution of the number of study sites among the UZs (ranging from 3 to 8).

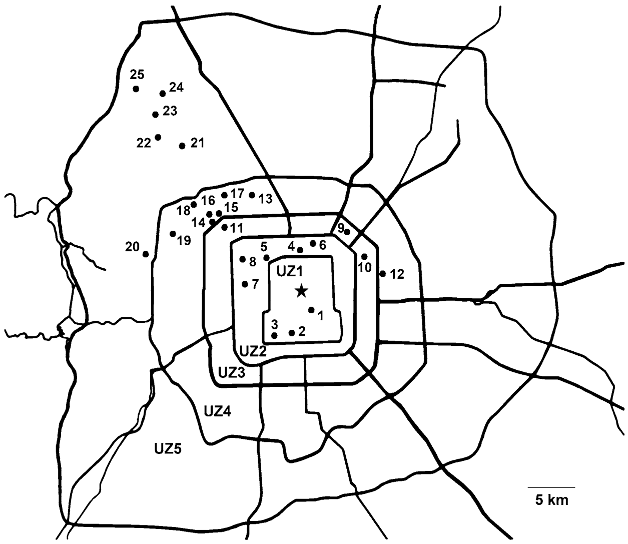

Fig. 1 Map of study sites in Beijing urban area. Urban center located at pentagon. *Lines* indicate main roads

Weevil survey

To reduce the confounding effects of different local habitats and urbanization, we chose to study organisms that dwell on tree trunks, and focused on the same tree species across many different sites. For this study, we selected willow trees (*Salix*), which are abundant and extensively distributed (at least 50 individual plants per site), in the Beijing urban area. We used band-shelter trapping to survey weevils, i.e., bands were wrapped around willow trunks at breast height (approximately 1.5 m above the ground). The band trap consisted of a 3-cm wide opaque synthetic fiber ribbon. One trap was installed on each willow trunk.

We sampled weevils every 2 weeks from early July to late October 2007, from late April to late September 2008 and from late April to mid-October 2009. We investigated 10 to 35 *Salix* individuals at each site, depending on the area of the site and the number of suitable and available willows. In 2007, all weevil species sheltering under the band traps were counted but not collected except for single individuals for identification in the laboratory. Bands were then retied at a new position, approximately 5 cm up or down from the former position. In 2008 and 2009, we collected all the individuals under band traps and then retied the bands. Damaged and missing traps were replaced at the next survey.

Table 1 Descriptions of the five urban zones divided basing on the ring-road system of Beijing

Urban zone	Description (Xie et al. 2007; Yang et al. 2005)	No. sites[a]	Range of DTC (km)[b]	Range of PIS3000[b]
1	Old city. Area within 2nd ring road which was the city of Beijing before 1949	3	0.5–5.6 (3.30)	0.78–0.91 (0.836)
2	Central business district between 2nd and 3rd ring roads; mainly developed between 1950 and 1980	5	5.3–7.7 (6.16)	0.82–0.90 (0.869)
3	Area between 3rd and 4th ring roads; mainly developed after 1980	3	7.9–11.9 (9.63)	0.62–0.73 (0.683)
4	Area between 4th and 5th ring roads; mainly developed after 1990	8	8.5–15.4 (12.71)	0.45–0.73 (0.600)
5	Area between 5th and 6th ring road; formerly cropland and grassland, with some development into residential/commercial districts after 2000	6	16.4–28.1 (23.20)	0.31–0.47 (0.380)

UZ1 represents the highest urbanized area, and *UZ5* represents the lowest urbanized one

[a] Number of study sites

[b] Numbers in parentheses are mean values. *DTC*: distance to urban center; *PIS3000*: proportion of impervious surface within 3 km (i.e., 6 × 6 km square)

All weevils were sorted into morphospecies and deposited at the Institute of Zoology, Chinese Academy of Sciences, Beijing. More than half of the morphospecies were formally identified as separate species by expert taxonomists. To construct a list of comparative abundance of weevil species among different urban zones, we standardized the abundance of each species at each site to 100 traps per year using the following equation:

$$SA_{ijk} = \frac{100 \times \sum A_{ijk}}{\sum T_{ij}}$$

where i is a certain survey year (=2007, 2008, or 2009); j is a certain study site; k is a certain weevil species; SA_{ijk} is the standardized abundance of k species at j site in i year; $\sum A_{ijk}$ is the total abundance of k species at j site in i year; and $\sum T_{ij}$ is the total valid traps (excluding damaged traps) at j site in i year. The average abundance in 3 years at j site was then calculated as $\sum SA_{ijk}$/(number of survey years).

Quantification of environmental variables

We recorded environmental variables and local characteristics of the sites as shown in Table 2. We used a GPS (Garmin-vista) to record the coordinates of each site (separated by pavements, fence and/or river from surrounding matrix), and to measure the perimeter and area of each site. We conducted a general field survey during September 2008 to estimate species richness of plants (including trees, shrubs, and herbs) at each site, and recorded the abundance of potential host plants (willows and poplars) using a unit scale of 50.

To quantify the proportion of impervious surface (PIS), we overlaid an image of the site and its surrounds with 60 × 60 grids (each grid 100 × 100 m) on Google Earth. Each study site was located at the center of the grid. We then counted the number of grids covered with impervious surfaces, and calculated the percentage. The PIS of the central 20 × 20 grids represented PIS in 2 km × 2 km squares (PIS1000); PIS of the central 40 × 40 grids represented PIS in 4 km × 4 km squares (PIS2000); and PIS of 60 × 60 grids represented PIS in 6 km × 6 km squares (PIS3000).

We measured the distance from each study site to the urban center (DTC) and to a possible nearest population source (DTP) with the software environment of Google Earth. The former was regarded as a comprehensive index of the degree of urbanization, the latter as an index of study sites' isolation from natural landscapes (Huang et al. 2010). We selected Tian An Men Square (39°54′20″N, 116°23′29″E) as the urban center point. The nearest possible population source is a large national forest park (39°59′51″N, 116° 9′3″E, area > 6000 ha, PIS3000 < 5%), located in the eastern part of the Xishan Mountains. This park is the nearest natural landscape to our study sites (approximately 6 km to the nearest site No. 20 in Fig. 1), and was assumed to be the nearest population source of the studied weevils. The vegetation in the Xishan Mountains is a mixture of coniferous and deciduous trees, including *Salix* (He et al. 1992).

Statistical analyses

Data on weevils were corrected by a sample-based rarefaction using EstimateS 8.2 (Colwell 2009) before other analyses were carried out. Diversity was measured using metrics of species richness (number of species per specified number of samples) and abundance (number of individuals per specified number of samples). In this study, we

Table 2 Environmental variables collected for each studied sites, and used in the partial least squares and the redundancy analyses

Scale	Code	Description
Landscape	DTC	Distance to urban center (km)
	DTP	Distance to a possible source population (km)
	PIS1000	Proportion of impervious surfaces, e.g., buildings, roads, in 2 × 2 km squares
	PIS2000	Proportion of impervious surfaces, e.g., buildings, roads, in 4 × 4 km squares
	PIS3000	Proportion of impervious surfaces, e.g., buildings, roads, in 6 × 6 km squares
Local	Age	Years since establishment of site
	Area	Area covered by park or greenbelt (m^2)
	Peri	Perimeter of park or greenbelt (km)
	SQRPA	Square root of perimeter/area ratio
	PLsp	Number of plant species in park or greenbelt in September 2008
	Wabun	Number of willow individuals in park or greenbelt in 2008
	Wsp	Number of willow species in park or greenbelt in 2008
	Pabun	Number of poplar individuals in park or greenbelt in 2008
	Psp	Number of poplar species in park or greenbelt in 2008

evaluated weevils from the lowest number of traps per site in the whole yield season (all survey times pooled). This number was 68 in 2007, 239 in 2008, and 177 in 2009. Thus, we use the expected number of species and individuals after rarefaction to 68 traps per site in the following analyses. Species richness and abundance at the same site were averaged over 2 or 3 years of samplings.

All the datasets were checked for normality using the Kolmogorov-Smirnov (or Shapiro-Wilk when df < 5) test prior to analysis and then normalized if necessary. Weevil abundance data was natural log-transformed. Data on seven of the environmental variables were log-transformed and the ratio of perimeter to site size was square root-transformed (see first column of Table 4).

One-way ANOVA was used to compare weevil species richness and abundance among urban zones and the LSD test was used for multiple pairwise comparisons following a significant ANOVA. These analyses were performed using SPSS 17.0 (SPSS Inc. 2008). Differences were considered as significant at $P < 0.05$.

Since several of the predictor variables (i.e., environmental variables) were highly interrelated (i.e., highly collinear), we used a partial least squares (PLS) regression with a nonlinear iterative partial least squares (NIPALS) algorithm to investigate relationships between each of the weevil diversity metrics (including species richness and abundance) and the environmental variables. These analyses were conducted using Statistica 8.0 (StatSoft Inc. 2007). PLS regression is particularly useful in ecological analysis where the predictors are strongly collinear (Carrascal et al. 2009). Moreover, it maximizes the covariance between the species diversity and predictors. In a biological context, this is more meaningful than using factor analysis separately on the species and environmental variables (Davis et al. 2007).

Only one significant component for each of the diversity metrics was retained. R^2 showed the explanatory capacity of the PLS regression models. The weights of each of the variables were used to interpret the meaning of the component. The contribution of each predictor was estimated by the squares of weight (Carrascal et al. 2009).

Changes in weevil species composition explained by environmental variables were analyzed with constrained ordination in CANOCO 4.5. The general structure of the species data was first tested using Detrended Correspondence Analysis (DCA). As the gradient length of first ordination axis was <3, we used Redundancy Analysis (RDA) to explain the differences in the species composition of weevils by environmental variables (ter Braak 1986). The effects of landscape and local variables were analyzed separately using Forward Selection. The level of significance was estimated with 999 Monte Carlo permutations.

Results

We captured 19 species of weevils during the 3-year survey period. In general, species richness was lower in the urban center (4 species in UZ1) and higher in the city outskirts (17 species in UZ5). The average abundance per 100 traps ranged from a low of 1.24 in UZ1 to a high of 674.46 in UZ5. The genus *Dorytomus*, which includes the four species, *D. setosus*, *D. roelofsi*, *D. occalescens* and *D. alternans*, was the most predominant group (Table 3).

The LSD multiple comparisons showed that weevil species diversity gradually decreased along an increasing gradient of urbanization from the outskirts to the urban center (Fig. 2). Species richness ($P < 0.0001$; Fig. 2a) and abundance ($P < 0.05$; Fig. 2b) were significantly higher at the peripheral zone than at the inner zone. There was no significant difference in species richness and abundance between the neighboring two or three urban zones (Fig. 2).

Table 3 Mean number of weevil individuals per 100 traps among urban zones

Species	UZ1	UZ2	UZ3	UZ4	UZ5
Dorytomus setosus		56.82	56.91	43.95	584.25
Dorytomus roelofsi	0.38	2.93	10.57	35.70	70.18
Dorytomus occalescens		0.59		0.18	12.19
Melanapion naga		5.91	0.56	0.62	1.72
Melanapion winteri			0.26	0.36	0.61
Asperogronops inaequalis		0.09		3.16	0.39
Ellescus schoenherri		0.34	0.21	1.31	0.65
Otiorrhynchinae sp.1[a]		0.21		0.23	1.11
Otiorrhynchinae sp.2	0.20	0.08			0.94
Otiorrhynchinae sp.3	0.59			0.12	1.18
Hyperinae sp.				0.04	0.69
Dorytomus alternans					0.09
Lepyrus japonicus	0.08			0.06	0.02
Zygopinae sp.1					0.30
Hypurus bertrandi					0.11
Tachyerges pseudostigma				0.13	
Cleoninae sp.1[b]					0.02
Cleoninae sp.2[b]					0.02
Smicronyx sp.		0.03			
Species richness	4	9	5	12	17
Total abundance	1.24	67.01	68.51	85.86	674.46

Abundance of each weevil species at each site was standardized to 100 traps per year. Mean number of weevils over 3 years was determined for each site, and then values from all sites within each zone were averaged. *UZ1–5*: 1st to 5th urban zone (detailed descriptions in Table 1)

[a] Because species were difficult to distinguish, mixed population of *Otiorrhynchinae* sp.1, sp.2 and sp.3 was recorded as the same morphospecies in the field in 2007

[b] Provisional identification

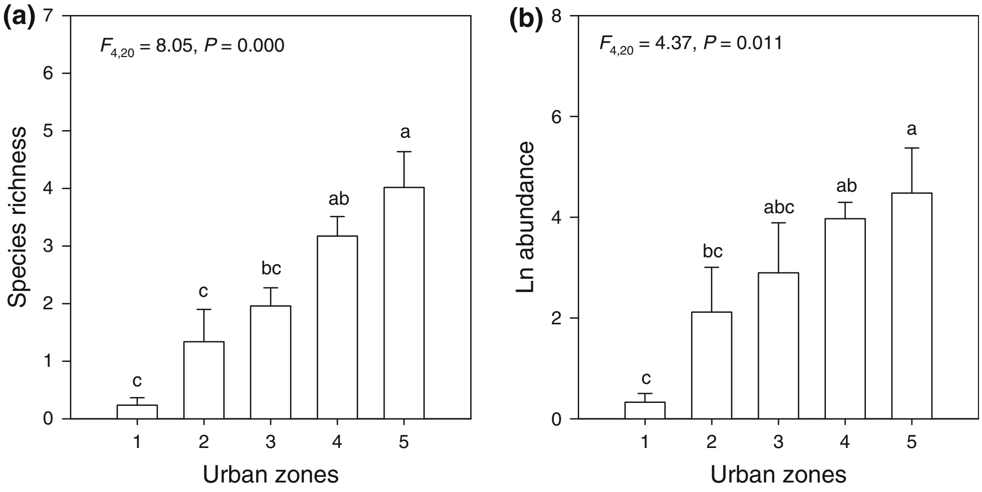

Fig. 2 Changes of weevil species richness and abundance (mean ± SE, based on 68 samples per site every year) along urbanization gradient (*UZ1*, urban center; *UZ5*, outskirts). Data were analyzed by one-way ANOVA followed by multiple pairwise comparisons (LSD test). *Different letters* above the *bars* indicate significant differences at $P < 0.05$

A PLS regression identified one significant ($P < 0.001$) factor of covariation among the 15 predictive variables explaining 64.2% of original variance in the number of weevil species (Table 4; Fig. 3). Landscape predictors accounted for 59.4% of variability in species richness. The species richness increased with the distance to the urban center (DTC), and decreased with the distance to the nearest possible population source (i.e., logPTC) and the PIS within 1–3 km (i.e., PIS1000, PIS2000, and PIS3000). Local variables accounted for only 4.9% of explainable variance in species richness. Furthermore, each landscape predictor made a greater contribution (as represented by the squares of weight) than that of each local variable (Table 4).

The PLS regression identified the significant ($P < 0.0001$) factor of covariation explaining 48.6% of original variance in the weevil abundance (Table 4; Fig. 3). Most of the explainable variance (43.9%) was related to landscape variables, whereas only 4.7% of the variability was accounted for by local variables.

Among all the significant variables (squares of weights > 0.05 in Table 4), DTC was the best predictor for species richness ($R^2 = 0.652$, $P < 0.001$) and abundance ($R^2 = 0.440$, $P < 0.001$), followed by PIS2000 (for species richness, $R^2 = 0.554$, $P < 0.001$; for abundance, $R^2 = 0.397$, $P < 0.001$). To predict how the diversity of willow trunk-dwelling weevils declines along an urbanization gradient, we simply estimated that, (1) within a 30-km limit of the urban center, the species richness and abundance might be reduced by 0.9 species and 59.3% of individuals per 5 km from outskirts to the urban center; and (2) the species richness and abundance might be decreased by 1.2 species and 72.4% of individuals per 20% PIS2000 increase from the sparsely urbanized area to the highly urbanized area. These estimations were based on the linear regression models in Table 5.

Table 4 Predictor weights of partial least squares regressions (PLSR)

	Species richness	Ln abundance
Landscape variables		
DTC	**0.475**	**0.454**
LogPTC	**−0.424**	**−0.432**
PIS1000	**−0.368**	**−0.384**
PIS2000	**−0.438**	**−0.431**
PIS3000	**−0.437**	**−0.420**
Local variables		
SQRPA	−0.026	−0.066
LogArea	0.003	0.013
LogPLsp	−0.147	−0.122
LogWabun	0.005	0.001
Wsp	−0.128	−0.194
LogPabun	0.049	0.012
Psp	0.052	0.074
LogWPabun	0.041	0.035
WPsp	−0.029	−0.047
Log(LogAge)	−0.171	−0.177
R^2 by the whole factor	0.642	0.486
Contributions by categories of variables (R^2)		
Landscape variables	0.594	0.439
Local variables	0.049	0.047

Weights with squares >0.05 are shown in bold type

Number of species and individuals used in PLSRs were based on rarefaction to 68 samples per site every year. Abbreviations of environmental variables are as in Table 2. LogPtoC, log ratio of DTP to DTC; WP, sum value of willow and poplar

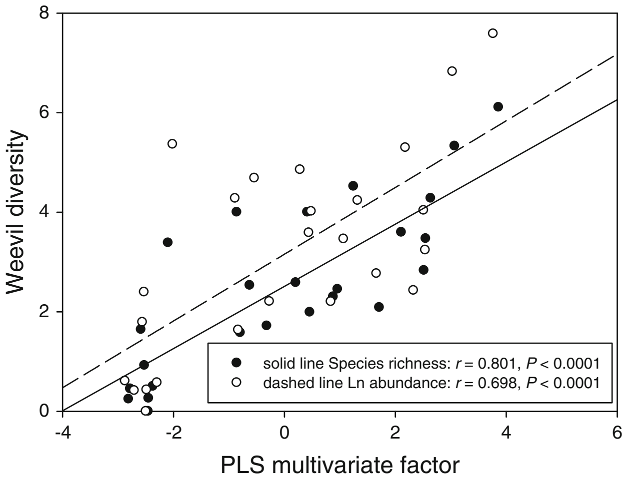

Fig. 3 Relationship between weevil diversity (based on 68 samples per site every year) and multivariate gradient obtained in partial least regression analysis. Species richness: $y = 2.510 + 0.625x$; abundance: $y = e^{3.156\ +\ 0.671x}$

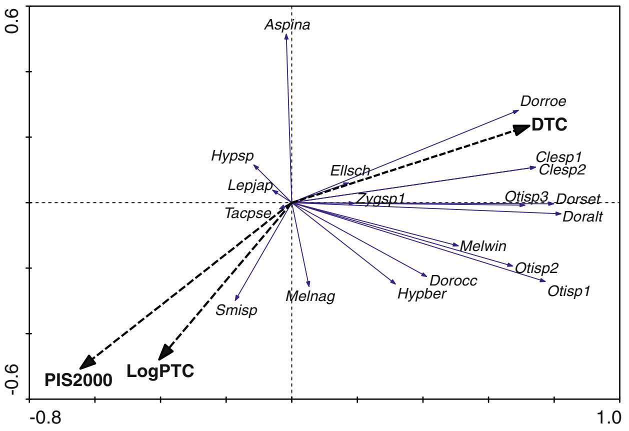

Fig. 4 RDA biplot for weevil species composition using significant ($P < 0.05$) explanatory variables at landscape level. Species abbreviations: Dorset (*Dorytomus setosus*), Dorocc (*Dorytomus occalescens*), Dorroe (*Dorytomus roelofsi*), Aspina (*Asperogronops inaequalis*), Melnag (*Melanapion naga*), Melwin (*Melanapion winteri*), Ellsch (*Ellescus schoenherri*), Doralt (*Dorytomus alternans*), Hypber (*Hypurus bertrandi*), Tacpse (*Tachyerges pseudostigma*), Smisp (*Smicronyx* sp.), Zygsp1 (Zygopinae sp.1), Otisp1 (Otiorrhynchinae sp.1), Otisp2 (Otiorrhynchinae sp.2), Otisp3 (Otiorrhynchinae sp.3), Lepjap (*Lepyrus japonicus*), Clesp1 (Cleoninae sp.1), Clesp2 (Cleoninae sp.2) and Hypsp (Hyperinae sp.). Abbreviations of environmental variables are as shown in Table 2

In the RDA with five landscape variables as explanatory variables, a total of 63.6% of the weevil species and 100.0% of the species–environment variation were accounted for by the first two axes. Three landscape variables, i.e., DTC, LogPTC, and PIS2000, were significant (DTC: $P = 0.002$, $F = 11.49$; LogPTC: $P = 0.04$, $F = 5.44$; PIS2000: $P = 0.028$, $F = 5.87$). The species biplot (Fig. 4) showed that the most common and abundant species *D. roelofsi* and *D. setosus*, as well as other species like *Ellescus schoenherri*, *D. alternans*, Cleoninae spp., *Melanapion winteri* and Otiorrhynchinae spp. were associated with sites with a lower PIS and those that were distant from the urban center. None of the local variables significantly explained variation in weevil species composition.

Discussion

The species diversity of trunk-dwelling weevil species showed a gradual decline along an increasing gradient of urbanization in Beijing metropolitan areas. Variables at the landscape level were more strongly correlated with this pattern than those at the local level. The species richness and abundance of weevils were lower in inner urban areas where the habitat remnants had a high PIS, and higher at outer areas in urban habitats with a low PIS. Species richness and abundance was poorly predicted by plant species richness, willow tree abundance, or site size. These results suggest that there is a negative relationship between urban expansion and weevil diversity. This has profound implications for urban wildlife conservation.

Patterns of change associated with urban expansion

As anticipated, species diversity of willow trunk-dwelling weevils declined along a gradient of increasingly intensive

Table 5 Simple linear regressions of species richness and abundance of trunk-dwelling weevils plotted against significant predictors

Significant predictors	Species richness			Ln abundance		
	Corr. Coef.	R^2	P	Corr. Coef.	R^2	P
DTC	0.180	0.652	<0.001	0.180	0.440	<0.001
PIS2000	−6.242	0.554	<0.001	−6.435	0.397	<0.001
PIS3000	−6.331	0.550	<0.001	−6.381	0.376	0.001
LogPTC	−2.371	0.518	<0.001	−2.533	0.398	<0.001
PIS1000	−4.680	0.391	<0.001	−5.106	0.314	0.004

Species richness and individuals (Ln-transformed) of willow trunk-dwelling weevils used in simple linear regressions were based on rarefaction to 68 samples per site every year. Significant predictors refer to those in bold (squares of weights were >0.05) in Table 4 urbanization. This result is consistent with many previous studies of upper-layer visitors and under-layer dwellers in large cities (urban population > 1 million), such as bumble bees in Stockholm (Ahrné et al. 2009), butterflies in the Greater Boston Area (Clark et al. 2007), wasps and bees in Belo Horizonte (Zanette et al. 2005), and carabids in Hiroshima (Ishitani et al. 2003). However, it is not consistent with studies of under-layer dwellers in small cities (urban population < 1.0 million), such as ground dwellers in Debrecen (Hornung et al. 2007; Magura et al. 2010) and Helsinki (Alaruikka et al. 2002). The differences in patterns of arthropod diversity between small and large cities imply that the size of the urban area is an important factor in biodiversity in urban landscapes, as indicated in avian studies (Sorace and Gustin 2009).

Our results showed that species richness and abundance of weevils decreased from the outermost to the innermost urban zones. However, this change was very gradual, and there were no significant differences among two or three neighboring urban zones (Fig. 2 and Table 3). This pattern can be explained by the pattern of Beijing's expansion, and suggests that there is a negative relationship between the extent of urbanization and weevil diversity. However, there are few reports describing this type of pattern. To test the hypothesis that the extent of urbanization is associated with the level of biodiversity, we need further studies across taxa in cities with various degrees of urbanization.

Factors that affect urban biodiversity

The change pattern of willow trunk-dwelling weevil diversity was strongly associated with the PIS at multi-scales (Table 4 and 5). PIS is generally used as a metric of urban matrix (McKinney 2002). This result is consistent with those of many previous studies across a wide range of taxa, such as flower visitors (Ahrné et al. 2009; Koh and Sodhi 2004; Öckinger et al. 2009), ground carabids (Sadler et al. 2006), birds (Palomino and Carrascal 2007), and amphibians (Hamer and McDonnell 2008). A possible explanation is that human-made structures in the urban matrix may influence and transform habitat qualities. As urban areas expand, the PIS dramatically increases as the amount of natural vegetation decreases (Raupp et al. 2010). Habitat fragmentation is also associated with the urbanization process, resulting in patches dissected into various sizes and shapes, and leaving trees as relatively isolated individuals in the urban matrix (Rickman and Connor 2003; Yasuda and Koike 2009). Subsequently, habitat quality becomes degraded while air pollution (Hao et al. 2000), traffic noise (Li and Tao 2004), and land surface temperatures increase (Ouyang et al. 2007). These effects of urbanization can be alleviated by forests (Yang et al. 2005). Invertebrates that live on bark, such as psocids and spiders, are affected by air pollution (Gilbert 1971; Roland 2004). The urban matrix (e.g., pavement) can be dangerous for weevils, e.g., *Dorytomus* spp. to cross. Therefore, if a species moves from a habitat in a more rural area into one dominated by urban matrix, its mortality rate can increase (Huang et al. 2010).

In this study, distances to the urban center and to a possible nearest population source were good predictors of weevil diversity (Tables 4 and 5). This may represent a positive relationship between distance from disturbance and biodiversity, a so-called 'isolation' effect. Our results showed that weevil diversity was likely to be higher at sites further from the urban center and sites with lower PIS (Fig. 4). When discussing the isolation of a given habitat, the mobility of the focal arthropods should be considered (Denys and Schmidt 1998). Weevils as a group are known to be sedentary (Nigg et al. 2001; Pierre and Hendrix 2003; Toepfer et al. 1999) and seldom disperse further than 1 km (Sharma and Amritphale 2007). Our results suggest that weevils may not be successful colonizers in the urban core due to isolation. Another explanation for the observed pattern may be that the decreased species diversity of trunk-dwelling weevils in inner urban areas was due to local disturbances (e.g., air pollution, visitor trampling). In general, population density (Wang et al. 2007), road density (Zhang et al. 2002), air pollution (Hao et al. 2000) and land surface temperature (Ouyang et al. 2007) increase from the outskirts to the urban center in Beijing.

Resource accessibility (Koh and Sodhi 2004; McFrederick and LeBuhn 2006), food quality (McFrederick and LeBuhn 2006), and the local regime (Kearns and Oliveras 2009) affect the types and abundance of flower visitors, whereas site size and woodland cover affect ground dwellers (Magura et al. 2010; Niemelä and Kotze 2009; Sadler et al. 2006). Surprisingly, our results showed that plant species richness, willow tree abundance, size of study sites, and other local variables did not explain variations in species richness and abundance of trunk-dwelling weevils (Table 4). This may be because the weevils studied here depend only on a single tree (and its immediate vicinity) for all their life stages, while flower visitors and ground dwellers require multiple habitats. The *Dorytomus* weevil that was predominant in our assemblages (Table 3) feeds on catkins of *Salix* at the larva stage, pupates in the soil under the host plant, then aestivates in curling bark of the host plant at the adult stage (Huang et al. 2010). This may explain, at least in part, why the abundance of potential host plants and site size were not related to variations in weevil abundance. Another explanation is that the effects of local variables were masked by those of urbanization metrics at landscape scales. The potential confounding effects of scale arise from the fact that many sites in inner zones are larger than those in outer zones and contain more willow trees.

Implications for conservation

Our study showed that plant species diversity and site size are poor predictors of weevil diversity in Beijing. However, this does not mean that they are not significant for weevil conservation in urban ecosystems. In fact, many studies have suggested that they are fundamentally important factors (Koh and Sodhi 2004; Prugh et al. 2008). In this study, the weevil species richness and abundance were higher at site No. 7 (Fig. 1) in UZ3 than at the other sites in the same urban zone and at many sites in other zones. This was partly attributed to the plant species diversity and size of this site.

Most ecological processes and interactions occur on spatial scales that are much larger than that of a single habitat (Steffan-Dewenter et al. 2002). Our results agree with this point, and implied that landscape structure is an important factor in ecosystem function of urban forests. To maximize the conservation value of the existing urban forests in Beijing, efforts should not only focus on local vegetation planting, but also on optimizing the structure of the urban landscape. The PIS should be restricted, e.g., to 70%, in inner urban areas, as there was no significant difference in species diversity between in UZ3 and in other zones (Fig. 2). Previous studies have shown that the probability of species extinction increases rapidly when the amount of matrix exceeds 70% (Fahrig 2001, 2002). Isolation is another important determinant of weevil species diversity, as shown by our results and those reported elsewhere (Davis et al. 2007; Minor and Urban 2009). Therefore, increasing the connectivity, e.g., through building urban domestic gardens (Gaston et al. 2005a, b; Pryke and Samways 2009), parks, and green corridors (Li et al. 2005) between urban remnants and natural landscapes in the city outskirts may be another important approach to maintain biodiversity.

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