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Degree of urbanization influences the persistence of *Dorytomus* weevils (Coleoptera: Curculionoidae) in Beijing, China

Dingcheng Huang[a,c], Zhimin Su[a,c], Runzhi Zhang[a,b,*], Lian Pin Koh[d]

[a] Key Laboratory of Zoological Systematics and Evolution, Institute of Zoology, Chinese Academy of Sciences, No. 1 Beichen West Road, Chaoyang District, Beijing 100101, PR China
[b] State Key Laboratory of Integrated Management of Pest Insects and Rodents, Institute of Zoology, Chinese Academy of Sciences, No. 1 Beichen West Road, Chaoyang District, Beijing 100101, PR China
[c] Graduate University of Chinese Academy of Sciences, 19A Yuquan Road, Shijingshan District, Beijing 100049, PR China
[d] Institute of Terrestrial Ecosystems, ETH Zürich, Universitätstrasse 16, Zürich 8092, Switzerland

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ABSTRACT

As degree of urbanization continues to increase, a better understanding of the relationship between degree of urbanization and level of biodiversity is important for developing strategies to mitigate detrimental impacts of urbanization and to build sustainable cities. *Dorytomus* Gemar weevils are host specific on *Salix* L. and *Populus* L. trees which are commonly used for urban afforesting and greening and abundant in Beijing metropolitan area which can be divided into five concentric zones. We aim to reveal their distribution pattern and identify important determinants of their persistence in those zones. Our results showed that *Dorytomus* species number and abundance decreased gradually from outskirt to urban center. This pattern could be predicted by built-up ratio within 1–3 km, distance to urban centre and to a possible nearest population source in outskirt, but not by hostplant species number and abundance, habitat size and shape measured at habitat scale. The results indicate that (i) there is a negative relationship between degree of urbanization and *Dorytomus* species persistence in urban areas; (ii) efforts for *Dorytomus* weevil conservation should not only focus on remnant revegetation, but also be directed to regulate the ratio of built-up area and minimize isolation from nearby occupied patches; and (iii) built-up ratio in inner city should be lower as urban sprawls. To better understand the relationship between urbanization degree and species persistence and to offer realistic suggestions for urban landscape planners, further research involving multiple taxa and the synthesis of the ecological responses of different taxonomical groups are needed.

1. Introduction

Urbanization contributes to serious environmental problems including the loss of native biodiversity, ecosystem goods and services (Czech et al., 2000; Grantz et al., 2003), and human health issues (World Bank, 2007). Global urban population is projected to increase from 3.2 billion in 2005 to 6.4 billion in 2050 (United Nations, 2008). Thus, a better understanding of the relationship between the degree of urbanization and level of biodiversity is important for developing strategies to mitigate potential detrimental impacts of urbanization on native biodiversity, and to build sustainable cities.

Urban ecology has gained prominence as an important research field over the past decade. Notably, studies employing qualitative comparative approaches reveal that species diversity in urban zones is typically lower than in suburban or rural areas (Mckinney, 2002). Furthermore, factors such as habitat loss (Faeth and Kane, 1978), isolation (Denys and Schmidt, 1998; Koh and Sodhi, 2004), resource removal (Koh and Sodhi, 2004; McFrederick and LeBuhn, 2006), patch characteristics (Ahrne et al., 2009; McFrederick and LeBuhn, 2006) and human disturbance (Hartley et al., 2007; Sadler et al., 2006) are important determinants of species persistence in urban areas. To understand the ecological processes underpinning the effects of urbanization on biodiversity, various approaches have been used to model interactions between environmental variables and species persistence during the process of urbanization. For example, a detrended correspondence analysis performed for woodland carabid assemblages in Birmingham, U.K. shows that site disturbance, soil penetrability, site size, amount of woodland and urban land within 5 km of the site are the most important predictor variables of beetle diversity (Sadler et al., 2006). A multiple linear regression analysis reveals that the number of potential larval host plant species and isolation from forests are most important

* Corresponding author. Tel.: +86 10 64807270; fax: +86 10 64807099.
E-mail addresses: huangdc@ioz.ac.cn (D. Huang), suzm@ioz.ac.cn (Z. Su), zhangrz@ioz.ac.cn (R. Zhang), lian.koh@env.ethz.ch (L.P. Koh).

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in explaining butterfly distribution patterns in Singapore (Koh and Sodhi, 2004). A common challenge in these studies is to disentangle the potential confounding effects of predictor variables on biodiversity, which are often not independent from one another (i.e. collinear).

Beijing has been experiencing a rapid urbanization for over two decades due to China's booming economy (Wu et al., 2006) and is now the second largest megacity in China with 14.39 million urban inhabitants in 2008 (National Bureau of Statistics of China, 2009). Among major cities in the world, Beijing represents one of the worse-case scenarios in terms of the severity of environmental impacts (World Bank, 2007), partly resulting from local urbanization (Song et al., 2006). However, the biodiversity consequences of urbanization in Beijing have been poorly studied. Here, we conducted a field study to reveal the change pattern of *Dorytomus* Germar weevil assemblages along a core-periphery urbanization gradient in Beijing. We used *Dorytomus* weevils (Coleoptera: Curculionoidea) because (i) they are well known to be host specific (oligophagous) on plant species of *Salix* L. and *Populus* L. genera (Salicaceae) (Fjellberg and Bocher, 2006; Keys, 1916; Morris, 1998, 2002; Nozawa and Inari, 2005; Topp et al., 2002; Urban and Kopelke, 2004); (ii) their host plants are commonly used for urban afforesting and greening and abundant in Beijing urban green spaces (Beijing Gardening and Greening Bureau, 2000); (iii) they are of conservation interest as they are preys of urban insectivore birds (i.e. titmice) in early spring (Morris, 1998); (iv) and they are relatively easy to collect by band-shelter trapping (unpublished).

The main aims of our study are to (i) identify the key determinants of the persistence of *Dorytomus* weevils in Beijing as a fast-growing megacity, (ii) disentangle the effects of some important variables from resource removal (i.e. host plants), (iii) provide a preliminary insight into the relationship between degree of urbanization and species persistence in urban areas, (iv) predict the persistence of *Dorytomus* weevils in Beijing as urbanization continues, and (v) offer suggestions for urban planning and *Dorytomus* weevil conservation.

2. Methods

2.1. Study sites

Beijing metropolitan area is located in the northern part of North China Plain (39°54′N, 116°23′E), altitude of which is lower than 100 m (Wang et al., 2007). Its urban sprawl presents a typical concentric distribution pattern (Liu et al., 2002; Ouyang et al., 2007). Currently, there are five ring roads (Fig. 1). The outermost one (the 6th ring road) stretches about 50 km from east to west and 60 km from north to south. Generally, Beijing's urbanization was limited within the 2nd ring road before 1949; areas between the 2nd and 4th ring road have been developed since then; and areas between the 4th and 6th ring road that were formerly farmland have partly become residential or commercial districts since the 1990s (Li et al., 2005).

Based on this ring road system, the main urban area can be divided 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) (Fig. 1). Generally, these UZs present a decreasing urbanization gradient from UZ1 to UZ5 (Ouyang et al., 2007).

A total of 25 urban parks and greenbelts were chosen as study sites along a core-periphery gradient, from the urban centre approximately 30 km toward less urbanized area (Fig. 1). In 2007, we selected 21 sites: 3 in UZ1, 5 in UZ2, 1 in UZ3, 7 in UZ4 and 5 in

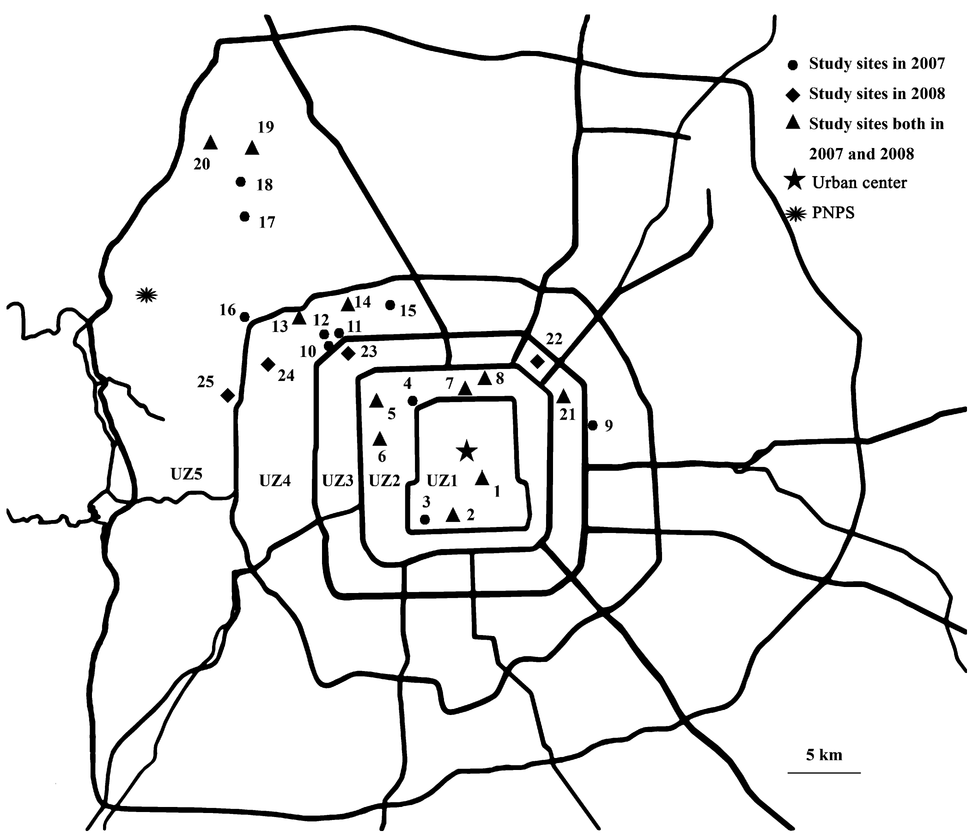

Fig. 1. The spatial arrangement of the study sites along the northwestern urbanization gradient in Beijing metropolitan area. Major highways were indicated with black lines. Numbers referred to IDs of studied sites listed in Appendix A. UZs referred to urban zones. PNPS refers to a large national forest park considered as the possible population source nearest to the study sites.

UZ5. In 2008, we surveyed 15 sites: 2 in UZ1, 3 in UZ2, 3 in UZ3, 4 in UZ4 and 3 in UZ5. There were 11 sites investigated in both years.

All sites are in the plain area, and range in size from 1.2 to 350 ha. They could all be characterized as managed green areas abundant in *Salix* spp. All of them are less than 60 years old since initial establishment except two sites, Summer Palace and Old Summer Palace (>250 years). To minimize the potential confounding effects from the age of surveyed tree, all selected sites contained at least 50 individuals of willows with a 10–20 cm diameter at breast height. Of the total six *Salix* species and seven *Populus* species in study sites, *Salix babylonica* L., *Salix matsudana* Koidz, *Populus* × *canadensis* Moench and *Populus tomentosa* Carr. are common species (see Appendix A for summary information).

2.2. Study organisms and sampling methods

Dorytomus weevil larvae usually feed on catkins (Fjellberg and Bocher, 2006; Keys, 1916; Morris, 1969, 1998, 2002; Nozawa and Inari, 2005; Urban and Kopelke, 2004) and occasionally on vegetative buds or growing shoots (Bland, 1997; Morris, 1998); pupae lie in thin surface soil, litter or root layer where host plants grow (Fjellberg and Bocher, 2006; Morris, 1998); adults are commonly not active or aestivate and overwinter under barks or in turf and litter under host plants (Fjellberg and Bocher, 2006; Morris, 1969, 1998, 2002) until mating season in early spring (Morris, 1969, 1998).

To the best of our knowledge, there are no previous studies on the ecology of this genus in the Beijing urban area. During a preliminary study in 2006, we found specimens of weevils, later identified as *Dorytomus roelofsi* Faust and *Dorytomus setosus* Zumpt, assembled under a band tied around the trunk of the willow tree, *S. matsudana* (band-shelter trapping method; see below). Since then, we have collected a total of four species (*Dorytomus alternans* Faust, *D. roelofsi*, *D. setosus* and *Dorytomus occalescens* Gyllenhal) in Beijing. Of these four species, the latter three have been found many times occurring gregariously under the barks of the willow trees, *Salix* × *aureo-pendula*, *S. babylonica* and *S. matsudana*, during our field work and from casual observations. *D. alternans* has been observed occurring on *S. babylonica* and *S. matsudana* with the other three weevil species.

Band-shelter trapping was used to monitor species diversity and population dynamics of *Dorytomus* weevils on willow trunks every 2 weeks. The trap was made using a strip of 3 cm wide opaque fiber band without any attractants, wrapped around a willow tree trunk (about 10–20 cm diameter at breast height) at approximately 1.5 m above the ground (unpublished). One trap was installed on each willow trunk. The number of traps at each site ranged from 10 to 35, depending on the area of the site and the number of suitable willow trunks.

In 2007, we recorded the number of adult individuals of each *Dorytomus* species sheltering under the band traps, and did not collect specimens except for a few individuals as voucher specimens for identification in the laboratory. Bands were then retied to a new position, about 5 cm either up or down from the former position. Each site was surveyed seven times from early July to late October. In 2008, we collected all the individuals under band traps and then retied bands to the same position. Each site was surveyed 10 times from late April to late September. Specimens were preserved with 99% ethanol, sorted to morphospecies in laboratory, identified by expert taxonomists and deposited at the Institute of Zoology, Chinese Academy of Sciences in Beijing.

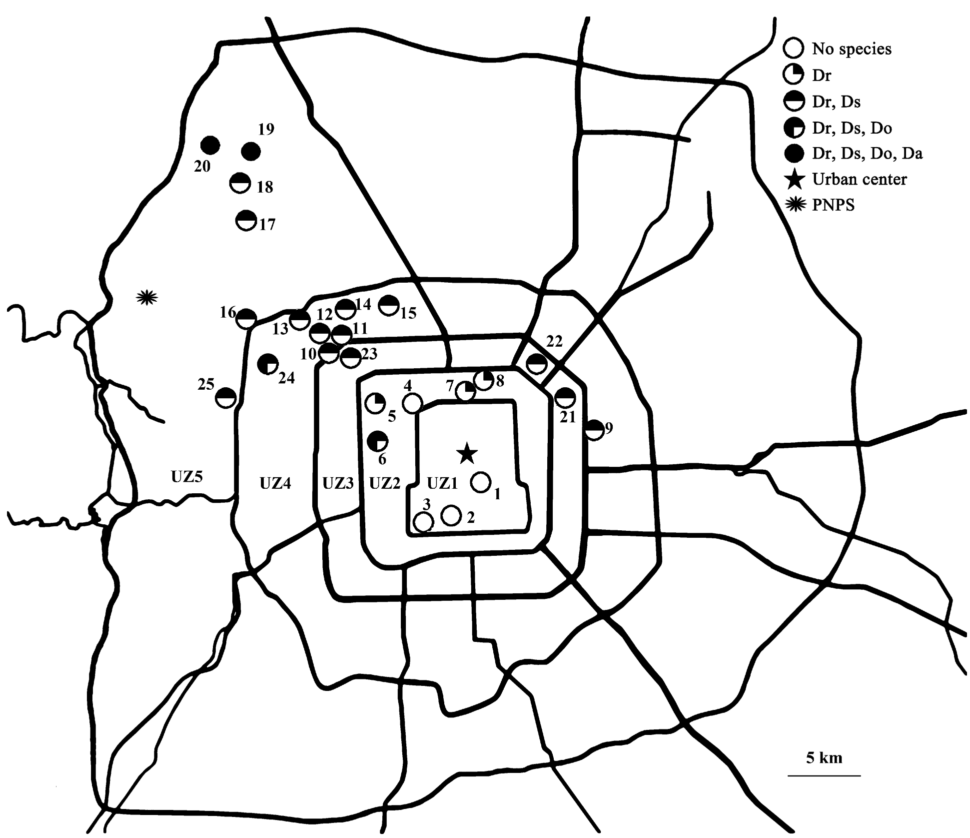

Fig. 2. Occupancy pattern of *Dorytomus* species at the study sites along the northwestern urbanization gradient in Beijing metropolitan area. Major highways were indicated with black lines. UZs referred to urban zones. Da, Do, Dr and Ds refer to *Dorytomus alternans*, *Dorytomus occalescens*, *Dorytomus roelofsi* and *Dorytomus setosus* respectively. PNPS refers to a large national forest park considered as the possible population source nearest to the study sites.

Table 1
One-way ANOVA for the number of species and abundance of *Dorytomus* weevils responding to urbanization gradient (Urban zones). Different letters behind standard errors in the same row indicate significant ($P < 0.05$) differences. LSD was used to make multiple comparisons.

Subject	Year	ANOVA		Multiple comparisons among urban zones ($M \pm$ S.E.)				
		F	P	1	2	3[a]	4	5
Number of species	2007	40.889	0.000	0.0 ± 0.0 b	0.4 ± 0.2 b	1	2.0 ± 0.0 a	2.4 ± 0.2 a
	2008	5.763	0.011	0.0 ± 0.0 c	1.5 ± 0.5 bc	2.0 ± 0.0 ab	2.3 ± 0.3 ab	3.3 ± 0.7 a
Log abundance of *Dorytomus setosus*	2007	7.870	0.002	0.000 ± 0.000 b	0.466 ± 0.466 b	0.000	1.494 ± 0.241 a	2.453 ± 0.427 a
	2008	3.465	0.050	0.000 ± 0.000	0.742 ± 0.742	1.586 ± 0.630	1.989 ± 0.427	3.298 ± 0.620
Log abundance of *Dorytomus roelofsi*	2007	6.989	0.003	0.000 ± 0.000 b	0.220 ± 0.220 b	0.489	1.642 ± 0.277 a	1.144 ± 0.360 a
	2008	2.287	0.132	0.000 ± 0.000	0.857 ± 0.235	1.256 ± 0.393	1.509 ± 0.433	1.946 ± 0.717
Log abundance of *Dorytomus* spp.[b]	2007	9.018	0.001	0.000 ± 0.000 b	0.686 ± 0.463 b	0.489	2.004 ± 0.234 a	2.496 ± 0.409 a
	2008	3.625	0.045	0.000 ± 0.000 c	1.250 ± 0.636 bc	1.753 ± 0.575 abc	2.112 ± 0.427 ab	3.323 ± 0.628 a

[a] Because there was only one study site in the 3rd urban zone in 2007, the 3rd urban zone did not join in the multiple comparisons in this year.
[b] *Dorytomus* spp.: the whole group of *Dorytomus* weevils.

2.3. Environmental variables and their measurements

We measured several environmental variables at habitat and landscape scales to detect the importance of environmental factors on *Dorytomus* species. GPS (Garmin-vista) was used to record the coordinate of each site (separated by pavements, fence and/or river from surrounding matrix), and to measure the perimeter and area of each site. To quantify the availability of host plants within each site, we visually estimated the abundance of willows and poplars. *Salix* and *Populus* trees were identified to species (Appendix A) using He et al. (1992). The numbers of *Salix* and/or *Populus* species at each site were also calculated.

Built-up ratio (BUR) has been used to quantify the degree of urbanization (Hahs and McDonnell, 2006; Magura et al., 2008). To estimate BUR within 1, 2 and 3 km of study sites (BUR1–3), we marked all site locations on Google Earth (V4.2), added an image overlay (a 3600-grid square picture) to their placemarks, counted the number of grids covering built-up areas (1 grid = 1 ha in the map) and then calculated the BUR (Appendix A). We separated study sites into three groups according to BUR1: highly urbanized area (BUR1 > 75%), moderately urbanized area (75% > BUR1 > 40%) and least urbanized area (BUR1 < 40%). Thus, there were six, seven and eight sites in highly, moderately and least urbanized area, respectively in 2007 and four, six and six sites in highly, moderately and least urbanized area, respectively in 2008.

We also measured the distances from study sites to urban centre (DTC) and a possible nearest population source (DTP) (Appendix A). Tian An Men Square (39°54′20.08″N, 116°23′28.77″E) was selected as the urban centre point. The possible nearest population source we considered is a large national forest park (39°59′50.52″N, 116°9′2.59″E, area > 6000 ha, BUR3 < 5%), which is located in the eastern part of Xishan Mountains and is one of the natural landscapes nearest to Beijing metropolitan area and our study sites. The Xishan Mountains cover by a mix of deciduous and coniferous forests growing *Salix* and *Populus* trees (He et al., 1992).

2.4. Data analysis

Because of occasional trap damage and unequal samples at different sites, we standardized the abundance of each *Dorytomus* species at each site to 30 traps per survey time and then pooled the data collected in each year within sites.

One-way ANOVA was used to test for differences in the number of species and abundance of *Dorytomus* weevils among different urban zones and among urban areas with different BUR1 (LSD for multiple comparisons), using sites as replicates. Principal component analysis (PCA) was performed on environmental variables. Principal components with eigenvalues >1 were selected. After the analysis using Quartimax with Kaisier normalization rotation, we removed variables with absolute loading <0.50. The remaining variables were then subjected to final principal factor analysis and factor scores for each site were given accordingly. To identify the potential factors affecting the persistence of *Dorytomus* weevils in urban areas, multiple linear regressions on the factor scores were run using stepwise selection method, and linear regression models were consequently established between the number of species or abundance of *Dorytomus* weevils as response variables, and the factor scores of each site as predictor variables. All variables were suitably transformed to approach normality prior to all analyses. All analyses were performed using SPSS 13.0. Results were reported at the 0.05 level of significance.

3. Results

3.1. Total assemblage and species distribution

A total of four species of the genus *Dorytomus* (*D. alternans*, *D. occalescens*, *D. roelofsi* and *D. setosus*) were captured in both years. We recorded 7,545 individuals in 2007 (not collected) and 23,972 individuals in 2008 (collected). The number of *Dorytomus* species per site ranged from 0 to 3 species in 2007 and from 0 to 4 species in 2008; the abundance of *Dorytomus* weevils at the study sites ranged from 0 to 5,242 in 2007 and from 0 to 15,260 in 2008. Across all the 25 sites, *D. roelofsi*, *D. setosus*, *D. occalescens* and *D. alternans* were found at 21, 18, 4 and 2 sites, respectively. In both years, no species was detected in the innermost urban zone (UZ1) while all species were found in the outermost one (UZ5). All of the 17 sites in UZ3–5 were occupied by no less than two species; in contrast, there were only one site occupied by three species, the others by no more than one in UZ1–2 (Fig. 2).

3.2. Effects of urbanization on the number of species and abundance

The number of species and abundance of *Dorytomus* weevils declined gradually from the outermost zone to urban centre in both years except the abundance of *D. roelofsi* in UZ5 which was not higher than that in UZ4 in 2007 (Table 1). In 2007, the number of species and abundance of *Dorytomus* weevils were significantly lower in higher urbanized zones (UZ2 and UZ1) than in less ones (UZ5 and UZ4). The difference in the number of *Dorytomus* species or their abundance between UZ4 and UZ5 was not statistically significant, neither was the difference in these two measurements between UZ1 and UZ2. In 2008, the number of species and abundance of total *Dorytomus* spp. were significantly lower in UZ1 and UZ2 than in UZ5, while *D. setosus* and *D. roelofsi* showed no significant variation in abundance among different urban zones (Table 1).

Table 2
One-way ANOVA for the number of species and abundance of *Dorytomus* weevils responding to urbanization gradient (BUR1). Different letters behind standard errors in the same row indicate significant ($P < 0.05$) differences. LSD was used to make multiple comparisons.

Subject	Year	ANOVA		Multiple comparisons among built-up ratio gradients ($M \pm$ S.E.)		
		F	*P*	100–75%	75–40%	40–0%
Number of species	2007	22.181	0.000	0.2 ± 0.2 c	1.4 ± 0.3 b	2.3 ± 0.2 a
	2008	11.943	0.001	0.5 ± 0.3 b	2.0 ± 0.3 a	3.0 ± 0.4 a
Log abundance of *D. setosus*	2007	9.215	0.002	0.000 ± 0.000 b	1.292 ± 0.381 a	2.001 ± 0.364 a
	2008	8.070	0.006	0.000 ± 0.000 b	1.632 ± 0.484 a	2.758 ± 0.528 a
Log abundance of *D. roelofsi*	2007	3.330	0.059	0.183 ± 0.183	1.141 ± 0.375	1.214 ± 0.288
	2008	5.932	0.016	0.401 ± 0.316 b	1.035 ± 0.214 b	1.950 ± 0.388 a
Log abundance of *Dorytomus* spp.[a]	2007	9.524	0.002	0.183 ± 0.183 b	1.710 ± 0.386 a	2.170 ± 0.333 a
	2008	7.564	0.007	0.332 ± 0.332 b	1.835 ± 0.394 a	2.845 ± 0.509 a

[a] *Dorytomus* spp.: the whole group of *Dorytomus* weevils.

Table 3
Selected principal components (PCs)[a] and their factor loadings.[b].

Variables[c]	2007			2008		
	PC1	PC2	PC3	PC1	PC2	PC3
BUR3	0.046	**0.968**	−0.013	0.102	**0.967**	−0.021
BUR2	−0.063	**0.956**	−0.012	−0.004	**0.957**	−0.035
DTC	−0.017	**−0.955**	0.104	0.049	**−0.947**	0.107
Log PTC	−0.027	**0.898**	−0.002	−0.079	**0.886**	−0.044
BUR1	−0.340	**0.853**	0.015	−0.318	**0.852**	0.127
DTP	0.056	**0.774**	0.230	0.237	**0.774**	0.137
Log A	**0.962**	0.059	0.018	**0.966**	0.057	−0.153
Log WP	**0.958**	−0.123	0.079	**0.980**	−0.058	0.104
Log W	**0.951**	−0.018	0.037	**0.966**	0.037	0.086
SQPA	**−0.894**	−0.090	−0.058	**−0.940**	−0.036	0.034
Log P	**0.832**	−0.262	0.132	**0.703**	−0.149	0.224
Psp	**0.668**	−0.044	**0.582**	**0.710**	0.029	**0.549**
Ssp	0.249	0.108	**0.857**	0.282	0.013	**0.815**
WPsp	**0.564**	0.027	**0.819**	**0.627**	0.026	**0.771**
RSSL[d]						
Eigenvalues	5.191	5.005	1.836	5.357	4.889	1.704
% of variance	37.077	35.748	13.113	38.264	34.919	12.168
Cumulative %	37.077	72.825	85.939	38.264	73.183	85.351

[a] The selection of principal components was based on Kaiser Criteria.
[b] Extraction method was principal component analysis. Loadings with absolute loading > 0.5 (in bold) were selected to calculate factor score for each site, others removed.
[c] BUR1–3: built-up ratio within 1–3 km radii; DTC: distance to urban centre; DTP: distance to a possible population source nearest to the study sites; Log PTC: log ratio of DTP to DTC; Log Area: log area of study site; SQPA: square root ratio of perimeter to area; Log W: log abundance of *Salix* trees; Log WP: log abundance of *Salix* and *Populus* trees; Wsp: the number *Salix* tree species; Log P: log abundance of *Populus* trees; Psp: the number of *Populus* tree species; WPsp: the number of species of *Salix* and *Populus* trees.
[d] Rotation sums of squared loadings by method of Quartimax with Kaiser Normalization.

The number of *Dorytomus* species was significantly higher in the least (BUR1 < 40%) and moderate (75% > BUR1 > 40%) urbanized areas than in the high (BUR1 > 75%) ones in both years (Table 2). Both of the abundances of *Dorytomus* spp. and *D. setosus* in highly urbanized areas were significantly lower than in moderate and least urbanized areas, while there was no significant difference in abundance of either species between moderate and least urbanized areas. The difference in abundance of *D. roelofsi* among different built-up ratio gradients was not statistically significant in 2007 but was significant in 2008 (Table 2).

3.3. Correlations with environmental variables

Through principal component analysis in 2007, three principal components were selected, which explained 85.9% of the total variance (Table 3). The first principal component (PC1) and the second (PC2) explained almost equivalent contribution rate of the total variance (37.1% and 35.7%, respectively), the third (PC3) 13.1%. PC1 mainly included variables representing the habitat characteristics (e.g. host plant abundance), PC3 reflected the number of host plant species (e.g. number of willow tree species), while PC2 was essentially a function of matrix (e.g. BUR3) and isolation metrics (e.g. DTP), reflecting the degree of urbanization at landscape level. The results of principal component analysis in 2008 were virtually identical to those in 2007 (Table 3), indicating that the study sites in 2008 had the same characteristics with those in 2007.

Stepwise regression analysis was conducted to reveal the potential relationships between environmental variables and the persistence of *Dorytomus* weevil in Beijing urban area. The final models included only PCS2 (the factor score of PC2), which accounted for about half of the total variance in the number of species and abundance of *Dorytomus* weevils except abundance of *D. roelofsi* (26.5%) in 2007 (Table 4). This supported that landscape-level factors (including matrix and isolation) may be important in influencing the spatial distribution of *Dorytomus* weevils in urban areas. Factor scores of the other principal components were eliminated during the stepwise selection process in both years.

4. Discussion

4.1. Distribution pattern of Dorytomus weevils along an urbanization gradient

Our study reveals a significant decrease of this group in both the number of species and abundance from outskirt toward urban centre in Beijing. Generally, willows in inner city areas were more poorly colonized by *Dorytomus* weevils than those near to outskirts. This result confirmed the generally observed pattern of declin-

Table 4
Stepwise regression analysis of the number of species and abundance of *Dorytomus* weevils with factor scores of the principal components.

	Year	Predictors[a]	Regression		Analysis of variance		
			Coefficient	R^2	*df*	*F*	*P*
Number of species	2007	PCS2	−0.336	0.698	1, 19	43.835	0.000
	2008	PCS2	−0.373	0.628	1, 13	21.970	0.000
Log abundance of *D. setosus*	2007	PCS2	−0.314	0.467	1, 19	16.660	0.001
	2008	PCS2	−0.457	0.668	1, 13	26.203	0.001
Log abundance of *D. roelofsi*	2007	PCS2	−0.180	0.265	1, 19	6.863	0.017
	2008	PCS2	−0.267	0.607	1, 13	20.096	0.001
Log abundance of *Dorytomus* spp.[b]	2007	PCS2	−0.319	0.476	1, 19	17.274	0.001
	2008	PCS2	−0.432	0.700	1, 13	30.265	0.000

[a] Factor score of the second principal component (PC2, see Table 3).
[b] *Dorytomus* spp.: the whole group of *Dorytomus* weevils.

ing biodiversity of a wide range of taxa in urban areas (Chace and Walsh, 2006; Hamer and McDonnell, 2008; Mckinney, 2002, 2008).

We were unable to make a comparison between the current *Dorytomus* assemblage in the Beijing urban areas with the historical community due to the lack of previous studies on this weevil group. The spatial pattern revealed in this study does, however, suggest a decline of *Dorytomus* weevil diversity. Specifically, the number of species and abundance of *Dorytomus* weevils increased gradually from urban centre to outskirt (Table 1 and Fig. 2). Our results further suggest that the *Dorytomus* species migrated away from inner urban patches with the expansion of Beijing's urban zones.

4.2. *Factors affecting the persistence of Dorytomus weevils in urban zones*

Resource availability and habitat characteristics are among the most likely factors affecting species persistence in urban areas (Ahrne et al., 2009; Koh and Sodhi, 2004; McFrederick and LeBuhn, 2006; Zanette et al., 2005). In contrast to these previous studies, we find none of the variables reflecting resource availability (e.g. willow abundance) or habitat characteristics (e.g. area of study site) could significantly explain the variance of the number of *Dorytomus* species and their abundance in each site. A possible explanation is that the effects of those variables (on resource availability and habitat characteristics) that we measured at the habitat scale were masked by the effects of the urbanization metrics that act on larger scales (Appendix B). Another potential confounding effect of scale arises from the fact that many sites (e.g. ID = 5–8) in inner zones are larger than those (e.g. ID = 15–18) in outer zones and contain more individuals of willows (Appendix A). An alternative explanation is that the *Dorytomus* species in this study system are not host specific (i.e. they ocuur on more than one *Salix* species), and different *Dorytomus* species can coexist with one another on the same willow species. These characteristics of *Dorytomus* species are also observed in previous studies (Fjellberg and Bocher, 2006; Morris, 1998; Nozawa and Inari, 2005; Topp et al., 2002; Urban and Kopelke, 2004).

Nevertheless, these patterns do not imply that host plant abundance and habitat area were not affected by urbanization. Indeed, they might be associated with urbanization at the landscape scale. Urbanization commonly changes land use, resulting in a decrease of vegetation cover and natural habitats, as well as an increase in the degree of habitat fragmentation. In our study, BUR1–3 increased linearly from outskirt to urban centre (Appendix B), which implied a potential decrease of host plant abundance, habitat loss and fragmentation due to urbanization at landscape scale (within 3 km of the site). A census data about the abundance and spatial distribution of plant species in Beijing urban area also shows that the abundance of willow and poplar trees generally decreases as the degree of urbanization increases (Beijing Gardening and Greening Bureau, 2000). This could partly explain why the number of *Dorytomus* species and their abundance were significantly associated with BUR1–3.

Recent studies have argued for the importance of considering the landscape context with respect to biodiversity maintenance (Fahrig, 1998, 2003; Prugh et al., 2008). The effects of the landscape matrix on species distribution patterns are increasingly evident across taxa and ecosystems (Prugh et al., 2008). The significant correlation between the number of *Dorytomus* species and BUR1–3 indicates that the urban matrix might impede the dispersal of *Dorytomus* weevils into highly urbanized areas (e.g. UZ1). This is in agreement with previous studies that reveal the effects of urban matrix on insect community composition and species richness (Ahrne et al., 2009; Kearns and Oliveras, 2009). Urban habitats are often fragmented and embedded in a matrix with predominantly vegetation-free land covers and high buildings that are inhospitable for *Dorytomus* weevils. Also, their narrow range of host plants might reduce their survival rate in remnant patches without willows or poplars. It is likely that the mortality rate would be higher in highly urbanized zones than in more rural areas (Fahrig, 2001). Furthermore, the probability of species extinction has been shown to increase rapidly above certain thresholds of the amount of urban matrix in the landscape (Berry et al., 1998; Fahrig, 2001; Ficetola and Denoel, 2009; Riley et al., 2005). In our study, the number of *Dorytomus* species and their abundance in UZ4–5 were conspicuously different from those in UZ1–2 where the amount of urban matrix was commonly higher than 70% (Table 1, Fig. 2 and Appendix A). This is consistent with a model predicting that probability of species extinction increases rapidly when the amount of matrix is over 70% (Fahrig, 2001).

Isolation is frequently supported as an important determinant of species richness in urban areas (Denys and Schmidt, 1998; Faeth and Kane, 1978; Hamer and McDonnell, 2008; Koh and Sodhi, 2004). On the other hand, there are also studies suggesting that isolation is not a good predictor of occupancy for most species in terrestrial habitat islands (Prugh et al., 2008). This may be because animal groups differ in response to the same isolation distance (Denys and Schmidt, 1998) and matrix (Fahrig, 2001). In our study, adult *Dorytomus* weevils are commonly inactive most of the time (Morris, 1998). The significant correlation of the number of *Dorytomus* species with DTP and PTC suggested that isolation might be another factor affecting their ability to penetrate core urban zones. All sites in UZ3–5 were occupied by *D. setosus* and *D. roelofsi*, while there were only one site by both of them, and the other sites by no more than one species in UZ1–2 (Fig. 2). A likely explanation could be that local populations at sites in inner

UZs might accept fewer immigrants (rescue populations) from large population sources than those in outer UZs, resulting in the extinction risk of the former being higher than the latter's. Moreover, ring roads and urban highways fragment Beijing's landscape into many blocks and exacerbate the disconnection of remnant habitats between zones (Fig. 1). Those pavements might work as speed bumps to reduce the immigration rate of sedentary *Dorytomus* weevils from source populations to remnant habitats in core urban areas.

The decline of *Dorytomus* weevil abundance may result from some local disturbances. This is possible as many studies in Beijing have suggested that, 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) generally decrease from inner city toward the outskirts. For instance, with the increase of population density and decrease of "natural" areas toward urban centre, trampling on remnant habitats can become more intensive, which might result in a less suitable soil surface for the pupation of *Dorytomus* weevils. This is in agreement with previous studies which suggest trampling due to recreational use as a factor affecting the ground beetle diversity in urban habitats (Lehvavirta et al., 2006). Furthermore, the heat island effect can induce changes of flowering phenology (Neil and Wu, 2006), and air pollution can indirectly affect bark-living insects (Gilbert, 1971). These two ways might directly affect host plants and thus result in negative effects on *Dorytomus* weevil abundance.

Species of small population size are less successful in colonizing an urban isolated habitat (Denys and Schmidt, 1998). Populations of *Dorytomus* species at all sites in UZ1–3 were less than 5% of the largest population in Cuihu Wetland Park which is 30 km from the Beijing urban centre. The populations of all species at the sites in UZ1 were not detected in both years, perhaps suffered from chronically low abundance due to local disturbance, habitat fragmentation and isolation from large populations in periurban area. *D. alternans* was only detected in the two farthest sites (Fig. 2). The populations of this species in highly urbanized landscape possibly undergo local extinctions due to extreme sensitivity to environmental disturbance and small population (Fenoglio et al., 2009; Rebele, 1994).

As PCS2 was virtually a function of habitat loss and fragmentation (BUR1–3), local disturbance (DTC), isolation (DTP), it could be regarded as a comprehensive index of urbanization, reflecting the degree of Beijing urbanization. Thus, the significant correlation of the number of *Dorytomus* species and their abundance with PCS2 (Table 4) could be interpreted as the degree of urbanization significantly influencing the persistence of *Dorytomus* weevils in Beijing urban zones. The observed patterns in our study might be mainly attributed to the combined effects of habitat fragmentation, inhospitable matrix, local disturbance and isolation associated with the continual urbanization of Beijing.

4.3. Implications for conservation, urban planning and further study

Our results showed that the number of *Dorytomus* species and their abundance decrease as urbanization degree increases when their host plants are abundant at habitat scale. This implied that in order to maximize the conservation value of existing urban "natural" areas, efforts should not only focus on remnant revegetation, but also be directed to regulate an appropriate amount of urban matrix and minimize isolation from nearby occupied patches and natural landscapes. The first priority for urban landscape planning should be to regulate the built-up ratio within certain limits under a matrix threshold value (e.g. 75% BUR1 for *Dorytomus* weevil conservation). However, species differ in response to habitat amount (Berry et al., 1998; Tscharntke et al., 2002). It is worthy and imperative to strengthen research on matrix threshold for urban biodiversity maintenance across taxa. We suggested built-up ratio in inner city be lower as urban sprawls. Greenbelts acting as corridors should be widened to offset the potential impacts of ring roads and highways on the urban landscape connectivity.

Habitat fragmentation and resource removal are two major ways that urbanization threatens species (McFrederick and LeBuhn, 2006). It is difficult to avoid resource removal in the process of urbanization (Denys and Schmidt, 1998). Therefore, to minimize the detrimental impacts of urbanization, a feasible and important thing we could do is to develop better urban plans that reduce the negative effects of habitat fragmentation. To meet this challenge, a model for the assessment of the potential effects of habitat fragmentation in planned urban landscapes is required to guide land use decisions. Our study approach may be helpful to build such model. In this study, we used host-specific taxa to detect the effects of habitat fragmentation in a system where their hosts are popular in urban areas and not associated with key predictor variables such as urbanization gradient, isolation, and amount of built-up areas at habitat scale, and employed a powerful tool to reduce the complexity of studied system.

Knowledge about the relationship between the degree of urbanization and biodiversity maintenance is of increasing importance, however poorly understood. Our study implied that *Dorytomus* diversity in inner urban areas decreased as the city expanded. Though we could not know the difference between the current community and their original status, we could predict their future pattern according to the final model. The detected pattern of *Dorytomus* weevils of today in UZ2 might be that of tomorrow in UZ3 if Beijing continues to sprawl its urban extent in old ways. To better understanding this relationship, further research involving multiple taxa and the synthesis of the ecological responses of different taxonomical groups are needed.

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Appendix A. Summary information of the study sites in Beijing metropolitan area in 2008.

ID	Sites	Urban zones	Area (ha)	DTC[a] (km)	DTP[b] (km)	BUR[c] within x km			*Salix* trees		*Populus* trees	
						x = 1	x = 2	x = 3	Species[d]	No[e]	Species[f]	No[e]
1	Changpuhe Park	UZ1	3.8	0.5	23.4	0.750	0.768	0.778	A	150	c	50
2	Taoranting Park	UZ1	59.0	3.8	23.9	0.783	0.811	0.824	A	800	c, g	100
3	You'anmen	UZ1	5.2	5.6	22.5	0.833	0.879	0.907	A, B	200	g	100
4	Xizhimen	UZ2	4.5	5.6	17.6	0.903	0.891	0.893	B, C	250	g	50
5	Zizhuyuan Park	UZ2	48.0	7.7	15.2	0.898	0.928	0.902	B, C	1200	c, g	200
6	Yuyuantan Park	UZ2	137.0	6.3	16.9	0.640	0.855	0.879	B, C	1500	a, c, d	600
7	Qingnianhu Park	UZ2	17.0	5.3	21.2	0.835	0.848	0.857	A, B, E	400	g	200
8	Liuyin Park	UZ2	17.5	5.9	21.1	0.743	0.741	0.816	A, B, C, E	1000	c, g	100
9	Chaoyangqiao	UZ4	2.0	8.5	29.4	0.578	0.626	0.683	B	100	g	50
10	Liulangzhuang	UZ4	6.3	12.2	11.4	0.535	0.612	0.660	B	2000	g	300
11	Haidianxi	UZ4	37.0	12.7	11.5	0.710	0.564	0.598	D	1000	b	100
12	Xinjiangongmen	UZ4	37.0	13.4	10.9	0.378	0.519	0.597	D	1000	b	100
13	Summer Palace	UZ4	293.0	14.9	9.4	0.305	0.469	0.492	A, B, C	4200	c, g	400
14	Old Summer Palace	UZ4	350.0	13.4	13.0	0.173	0.476	0.591	A	2000	g	1700
15	Wudaokou	UZ4	0.5	11.2	15.5	0.745	0.719	0.726	B, C	50		0
16	Xiangquanhuandao	UZ5	1.2	17.8	5.5	0.363	0.365	0.329	B	50	c, g	50
17	Tundian	UZ5	2.1	22.9	8.9	0.390	0.410	0.406	B, C	200	c	300
18	Rendazhongxue	UZ5	9.0	25.2	11.8	0.395	0.412	0.397	B, C	300	c	200
19	Shuikunankou	UZ5	3.5	26.3	12.0	0.398	0.373	0.349	B	300	g	200
20	Cuihu wetland Park	UZ5	100.0	28.1	11.6	0.143	0.194	0.308	A, B, C	2000	b, c, e, g	2000
21	Chaoyang Park	UZ3	320.0	9.1	28.5	0.450	0.675	0.726	A, C, F	5000	a, c, e, f, g	3000
22	Taiyanggong Park	UZ3	37.0	7.9	25.7	0.400	0.619	0.704	B, C	600	g	100
23	Wanliu	UZ3	35.0	11.9	11.7	0.538	0.603	0.618	B, C	500		0
24	Mentouxincun	UZ4	9.0	15.4	7.4	0.350	0.413	0.453	B, C	150	g	100
25	Nanxinzhuang	UZ5	1.6	16.4	6.8	0.463	0.456	0.468	B, C	100	g	50

[a] DTC: distance to urban centre.

[b] DTP: distance to a possible population source nearest to the study sites.

[c] Built-up ratio.

[d] A: *Salix × aureo-pendula*; B: *Salix babylonica* L.; C: *Salix matsudana* Koidz; D: *S. matsudana* var. pendula Schneid.; E: *S. matsudana* var *tortuosa* Vilm; F: *S. matsudana* var. *umbraculifera* Rehd.

[e] Number of individuals.

[f] a: *Populus alba* L.; b: *Populus × beijingensis* W.Y. Hsu; c: *Populus × canadensis* Moench; d: *Populus cathayana* Rehd.; e: *Populus davidiana* Dode; f: *Populus nigra* var. *italica* (Moench); g: *Populus tomentosa* Carr.

Appendix B. The full correlation matrix of all environmental variables.[a]

Variables[b]	DTC	DTP	Log PTC	BUR1	BUR2	BUR3	SQPA	Log Area	Log W	Log WP	Wsp	Log P	Psp
DTP	**−0.669**												
Log PTC	**−0.862**	**0.827**											
BUR1	**−0.733**	**0.464**	**0.656**										
BUR2	**−0.886**	**0.623**	**0.774**	**0.896**									
BUR3	**−0.912**	**0.683**	**0.802**	**0.827**	**0.979**								
SQPA	0.121	−0.169	−0.075	0.219	−0.021	−0.119							
Log Area	−0.118	0.172	0.086	−0.240	0.057	0.166	**−0.922**						
Log W	−0.038	0.106	0.026	−0.206	0.036	0.138	**−0.762**	**0.893**					
Log WP	0.069	0.065	−0.046	−0.308	−0.065	0.036	**−0.738**	**0.878**	**0.982**				
Wsp	−0.017	0.137	0.012	0.044	0.096	0.134	−0.286	0.287	0.303	0.305			
Log P	0.215	0.064	−0.084	−0.385	−0.204	−0.132	**−0.450**	**0.538**	**0.638**	**0.748**	0.174		
Psp	0.063	0.224	0.041	−0.209	−0.061	−0.011	**−0.548**	**0.550**	**0.572**	**0.635**	**0.421**	**0.694**	
WPsp	0.034	0.221	0.034	−0.120	0.007	0.060	**−0.515**	**0.517**	**0.541**	**0.585**	**0.788**	**0.558**	**0.890**

[a]Data from all sites in 2 years were used to make this correlation matrix. Values in bold indicate significant correlation (two-tailed, $P < 0.05$).

[b] Refer to Table 3 for variable descriptions.

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