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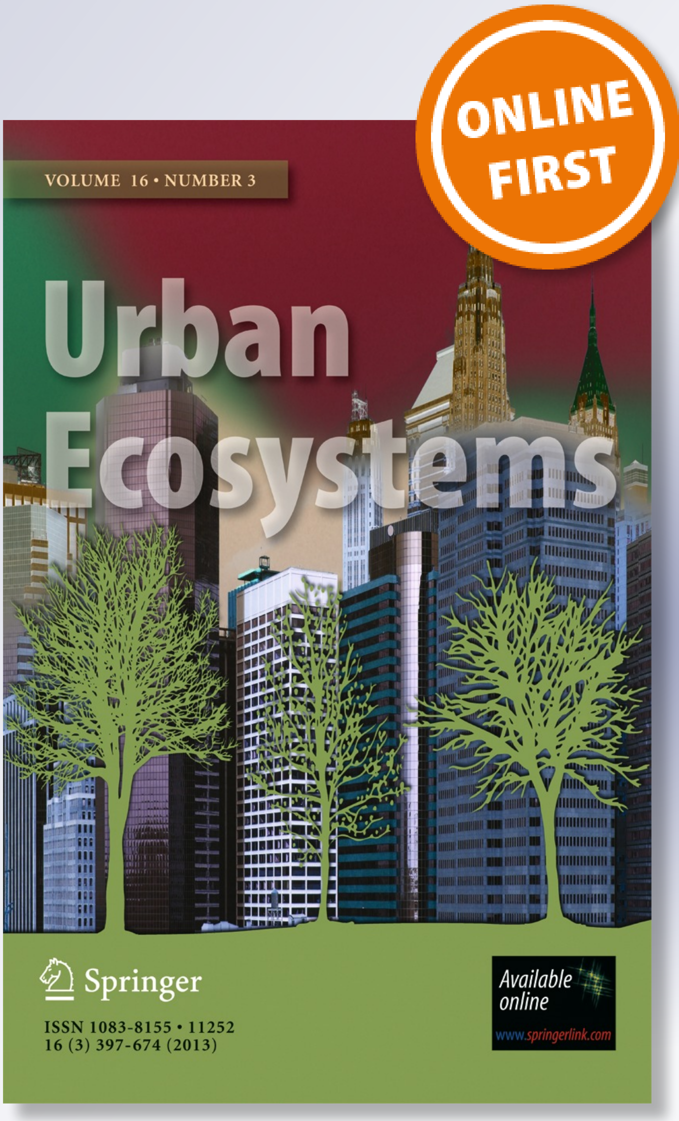


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# Dynamics of ruderal species diversity under the rapid urbanization over the past half century in Harbin, Northeast China

**Xiaoshuang Chen · Weibo Wang · Hong Liang · Xiaoli Liu · Liangjun Da**



**Abstract** Urbanization has resulted in obvious changes in plant species diversity. We analyzed the dynamics of ruderal species diversity in Harbin over the past half century using historical data collected in 1955 and data of the present spatial distribution in 2010–2011. The results show that, the number of ruderal species decreased from 611 to 175 with remarkable tendency of decreasing in perennial species and increasing in winter annual species in the past half century, which caused the shift of life form spectrum from perennial mono-dominant type to summer annual and perennial co-dominant type. Meanwhile, the proportion of tropical originated species increased and the proportion of temperate originated species decreased which were considered to relate with the increase of temperature in urban area during the past half century. Moreover, there was a distinct decrease of the proportion of aquatic and hygrophytic ruderal species while an increase of mesic and xeric ruderal species which suggested a drought trend in urban habitats that consistent with the change of land use characterized as decrease of natural water bodies and wetlands and increase of urban land. Comparison of ruderal species along urbanization gradient also got the similar results with the above results from analysis on temporal scales and confirmed the effect of urbanization on decreasing plant richness. Our results suggested that land use change combined with its effect on temperature and disturbance regimes in urban habitats preferred species with short life span, high drought tolerance, fast growth rates and high seed yields.

**Keywords** Land use change · Urbanization gradient · Species diversity · Adaptive strategy

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## Introduction

Contemporary urbanization and other types of human-associated land conversion are increasing at an unprecedented rate in many parts of the world (Seto et al. 2010; Romagosa et al. 2013; Currit and Easterling 2009). Aggregation of the urban population and high-density construction of urban roads and buildings results in changes in a city's illumination, temperature, precipitation, soil conditions and other ecological factors (Ren et al. 2003; Zhou et al. 2004; Liu and Diamond 2005; Robert and George 2006), and makes the urban area habitat appear heterogeneous (Zhao et al. 2006). These pronounced changes in the urban environment also lead to obvious changes in species diversity (Da and Ohsawa 1992; Pyšek et al. 2004; McKinney 2006; Burton et al. 2009). When they are widely distributed, and can complete the life cycle in urban areas without disturbance by human activities, ruderal species are an important part of urban vegetation (Nemoto 2006). Moreover, because of their high sensitivity and flexibility, ruderal species respond to the urban habitat heterogeneity and rapidly adapt to changing habitats by changing their morphology, physiology and behavior (Colliers and Bredenkamp 2000; Nemoto 2006; Dana et al. 2002). Thus, ruderal species are ideal to facilitate studies on the impact of urbanization on urban ecosystems and subsequent ecosystem response (Tian 2011).

Over recent years, ruderal species have gradually become a key topic of urban vegetation studies. From the 1970s onwards, there have been a large number of studies on ruderal vegetation in the United States and Europe, especially in Germany, the Czech Republic, Poland and other countries (Anning and Yeboah-Gyan 2007; Franceschi 1996; Hitchmough and Woudstra 1999; Benvenuti 2004). The above studies show that there is an obvious downward trend in ruderal species diversity from rural to urban areas. The number of native ruderal species in urban areas accounts for only 1/3 of those found in rural areas (Sharpe et al. 1986). The distribution pattern of ruderal diversity is correlated with soil water use and the frequency of human disturbance (Dana et al. 2002; Sarah and Zhevelev 2007). Most recent research suggests that under rapid urbanization, habitat change is an important environmental filter, and is essential for the distribution of ruderal species (Nicholas et al. 2009).

To date, the main focus of ruderal vegetation research in China, which is frankly in its infancy, has been arable land and alien invasive ruderal species. The former includes the analysis of biological and ecological characteristics of the occurrence, growth and succession of arable land ruderal species, dormancy and germination of arable land ruderal seed and the impact of different land use types on species composition (Guo and Li 1997; Qiang and Cao 2001; Ding et al. 2006). The latter has included research on invasive pathways and mechanisms, risk warning and measures to prevent alien invasive ruderal species as well as their impact on local ecosystems (Gao 2012; Li et al. 2001; Wu and Qiang 2003; Guo et al. 2004; Da et al. 2007; 2008). In addition to the above, the distribution pattern and phenotypic plasticity of ruderal species in urban and rural gradients in Shanghai were analyzed (Tian 2011; Cai 2012).

Urbanization is always accompanied by dramatic changes in land use and land cover (Foley et al. 2005; Houghton 1994; Hepinstall-Cymerman et al. 2013). The dramatic changes in land use and land cover, characterized by an increased area of impervious surfaces, leads to changes in species composition, vegetation structure and simplified vegetation vertical diversity (Robinson et al. 2005; Hepinstall-Cymerman et al. 2013). However, to date, there have been few studies on temporal dynamic changes in ruderal species diversity under urbanization.

Since China's reform and opening up in 1978, Harbin has experienced rapid development. Ruderal species diversity in Harbin was analyzed in 1955 (Baranov et al. 1955). Over the intervening 56 years, no up-to-date information was collected about the dynamics and present situation of ruderal species diversity in Harbin. The present study is an attempt to analyze the degree of dynamic change in ruderal species and to demonstrate the influence of urbanization on ruderal species and their subsequent adaptive strategies, using up-to-date data and the information collected for the earlier study (Baranov et al. 1955). We aim to answer the following questions: (a) How did climate and land use and land cover change over the past half century? (b) What is the current situation of ruderal floristic composition? (c) How has ruderal species diversity changed over the past 56 years? The present study will provide useful information for the local government to help them (1) improve urban ecosystem conservation and management and (2) construct a solid basis for further in-depth research on ruderal species dynamics.

## Study area

Harbin, the capital and largest city of Heilongjiang Province, is located on the southeastern edge of the Songnen Plain and serves as a key political, economic, scientific and cultural communications hub in Northeast China (Fig. 1). Harbin has a typical continental monsoon climate with a mean annual temperature of 5.2 °C and average annual precipitation of 569.1 mm. The soil in Harbin, called "black earth", is one of the most nutrient rich in all of China, making it valuable for cultivating crops and ruderal vegetation. The zonal vegetation is elm forest steppe. Harbin was founded by Russia in 1898 with the arrival of the Trans-Manchurian Railway. Since 1978, Harbin has experienced rapid urbanization. Like most cities in China, Harbin has been constructed from a central point, and extends radially outwards. The urban construction has followed a concentric circle pattern, with the characteristic "inner, mid and outer circles". In line with the study area of Baranov et al. (1955), the study area in the present study is within the Outer-Ring Road in Harbin, which covers an area of 591.7 km$^2$ and has an approximate population of 5.87 million. The urban habitat in Harbin has become increasingly heterogenous in the recent past because of the

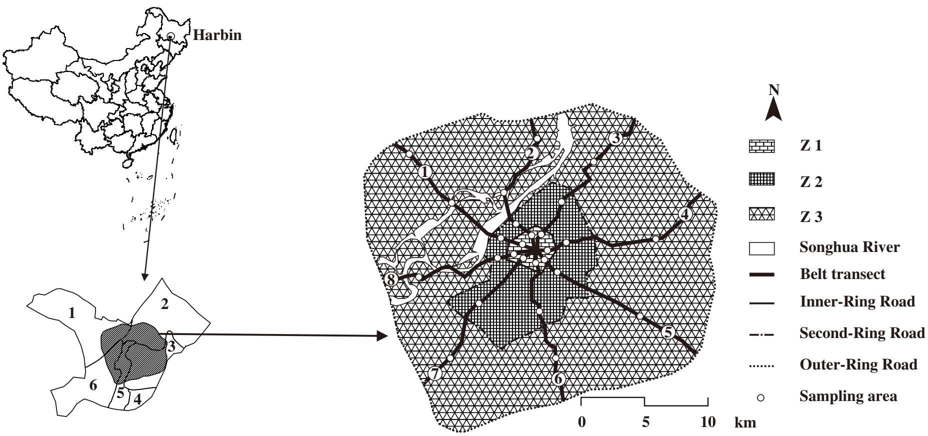


**Fig. 1** Study area (1, 2, 3, 4, 5 and 6 represent Songbei, Daowai, Xiangfang, Pingfang, Dongli and Nangang districts, respectively)

rapid urban development. The vast majority of current urban vegetation is thought to be non-native and, except for ruderal vegetation, most of the natural vegetation in the urban area has been devastated by the rapid urbanization.

## Methods

### Survey of ruderal flora

#### *Sampling methods*

Field data of ruderal species were collected by field survey from May to September in 2010 and 2011, thereby accounting for most of the ruderal vegetation growing season. The study area was divided into the inner zone (Z1: the area within Inner-Ring Road), mid zone (Z2: the area from Inner-Ring Road to Second-Ring Road) and outer zone (Z3: the area from Second-Ring Road to Outer-Ring Road), as defined by the urbanization gradient (Fig. 1).

The filed survey method applied in the present study, included two parts, i.e. surface survey and point survey. The surface survey was to make all the ruderal habitat types inside the Outer-Ring Road were surveyed, and the point survey was to make all the ruderal species in each sampling site were surveyed.

Base on the surface survey in the study area, we selected nine typical urban ruderal habitat types (i.e. road gap, lawn, soil abandoned land, gravel abandoned land, arable land, shrub-grassland gap, forest gap, wetland and tree pool). These urban ruderal habitats match those that have been considered in other studies carried out elsewhere (Tian 2011; Jiang 1993; Wang 2008; Zdeňka et al. 2011). Additionally, we selected a star-shaped array of 26 sampling sites with different ruderal habitat types, and each of these sampling sites included all, or portions, of the nine urban ruderal habitat types. There were three sampling sites on each of the star arms Z1, Z2 and Z3. Moreover, for this study we added an additional sampling site to arm 1 and arm 2, to account for the wetlands in both of them.

Base on the point survey, we selected all the ruderal habitat types occurred in each sampling sites. In each ruderal habitat, we surveyed the species found in the central zone of the ruderal habitat to removing the edge effect. We also recorded the light condition, soil condition, human disturbance and other environmental factors in the urban ruderal habitat when undertaking the field survey. Additionally, we recorded the ruderal species discovered outside of the sampling sites so that ruderal species were not missed, which meant all the ruderal species inside the Outer-Ring Road were surveyed.

#### *Data collection and analysis*

A species frequency index ($f$) was developed to calculate species occurrence frequency in Harbin. The species frequency was divided into four categories: no occurrence ($f$=0), accidental occurrence ($0<f\leq5$ %), medium occurrence ($5<f\leq10$ %), and widespread occurrence ($f>10$ %). Coefficients of 0, 1, 2, and 3 were used to describe the standardized values for four species frequency ranks. The species frequency index can be expressed as follows:

$$f_i(u_j) = \frac{g_i(u_j)}{\sum_{j=1}^{n} g_i(u_j)} \times 100\% (i = 1, 2, 3, \cdots, m; j = 1, 2, 3, \cdots, n),$$

where $i$ stands for a species, $j$ stands for a zone, $m=175$, $n=3$, $g_i(u_j)$ represents the proportion of the occurrence number of species $i$ in zone $j$ to the total occurrence number of species $i$ in all zones. We also carried out cluster analysis of the ruderal species based on Ward's method and Euclidean distance, using PC-ORD 5.0 software (Tian 2011).

We also included the historical survey data collected in 1955 by Baranov et al. (1955) in this study. Baranov et al. surveyed the same area as we did in 2010–2011. Moreover, the sampled area in 1955, which contained nearly all the ruderal habitat types at that time (i.e. road gap, lawn, abandoned land, arable land, shrub-grassland gap, forest gap, wetland and tree pool), was comparable with our present study. The data contained a large amount of information with for most species the scientific name and Chinese name of that time and the habitat. For this study, we redefined the family, genus and species of ruderal vegetation because there was a great difference between the plant classification system used in the historical data and the field data. We based the new classification on information from the Key of Plants of Northeastern China (Liu 1959), Dictionary of the Families and Genera of Chinese Seed Plants (Hou 1984), Flora Republicae Popularis Siniae (Editorial Committee of Flora Repubicae Popularis Siniae in China Academy of Science 1991), and Flora of Heilongjiang (Zhou 2001). For the areal type of ruderal vegetation we adopted Wu's definition (Wu et al. 2006), while we used the definition of alien species from previous research (Zheng and Pan 2012). Based on life history characteristics, the present study classified ruderal life form into perennial and annual according to the book of Chinese Vegetation (Wu 1980). Annual species were further divided into winter annual and summer annual. To analyze the dynamic changes in ruderal floristic composition over the past 56 years, we divided the ruderal species in 1955 and 2010–2011 into three groups (i.e. disappeared species, emerging species and remaining species). Disappeared species were those that were recorded only in 1955, while emerging species were those that were recorded only in 2010–2011. The remaining species were those that were recorded in both 1955 and 2010–2011.

## Analysis of the impact of urbanization

### *Climate change from 1957 to 2011*

We used temperature and precipitation data derived from the Harbin Statistical Yearbook (Harbin Statistical Bureau 2012) to analyze climate variation in Harbin.

### *Land use/cover change from 1976 to 2010*

To study the impact of urbanization on ruderal vegetation, we used a Landsat MSS image from 1976 (79-m spatial resolution) and a Landsat TM image from 2010 (30-m spatial resolution). We considered that these images were suitable for answering the research question. The Landsat images were acquired under clear and cloud-free atmospheric conditions. Multi-gated Landsat images were geo-registered with the most noticeable corresponding image control points, using a polynomial 2 transformation and the nearest neighbor resampling method, with precision kept at the 0.5 pixel level. The geometric boundary of the image was corrected by the remote sensing image processing system ENVI 4.8 after verification and matching. Based on the national classification system of land resources of China (Standardization Administration of China 2007), land use type was divided into arable land, urban land, forestry land, grassland and water body.

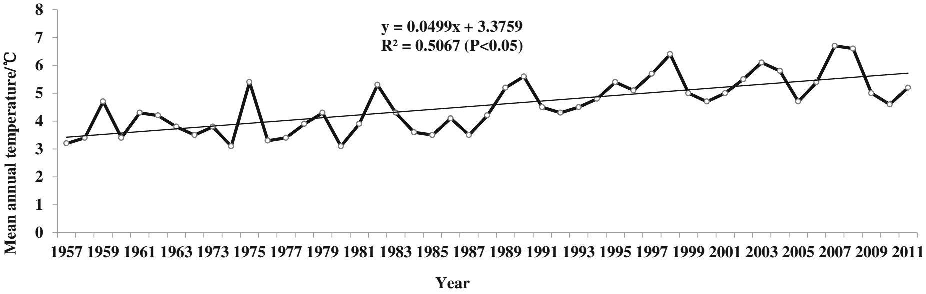


**Fig. 2** Mean annual temperature change in the study area from 1957 to 2011

## Results

### Changes in climate and land use/cover

#### *Variation in climate*

The variations in the mean annual temperature and precipitation in Harbin from 1957 to 2011 were analyzed using SPSS software (Zhang et al. 2010). The results indicated that, over the 54 years, the mean temperature showed a significant slight increase trend with a rate of 0.4 °C/10 years in Harbin (Fig. 2). Meanwhile, there was no obvious variation in mean annual precipitation (Fig. 3).

#### *Dynamic change of land use/cover*

Acquired by GIS techniques (Ren et al. 2012; Guan et al. 2008), land use change extent and land use change matrix are displayed in Fig. 4 and Table 1, respectively. 62.6 % of the total area changed significantly from 1976 to 2010. Arable land decreased by 36.5 %, urban land and grassland increased by 100.8 and 24.1 km$^2$ from 1976 to 2010, respectively. A total of 66.1 % of land that was arable land in 1976 was converted to other types, of which 54.7 % was converted to urban land. Of the land classified as arable in 2010, 44.6 % had been converted from forest and grassland by artificial reclamation. Although there was an obvious increase in grassland, most of it in 2010 had been converted from urban land and forest land in parks, and changed to artificial lawn. The water body area increased slightly, but 50.6 % of it in 2010 was converted from urban land, grassland, arable land and forestry land.

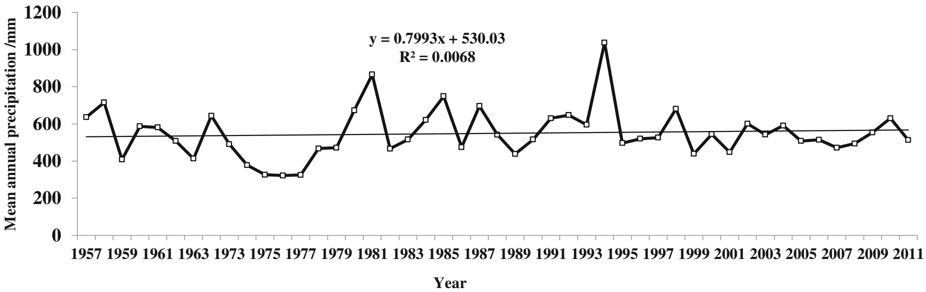


**Fig. 3** Mean annual precipitation change in the study area from 1957 to 2011

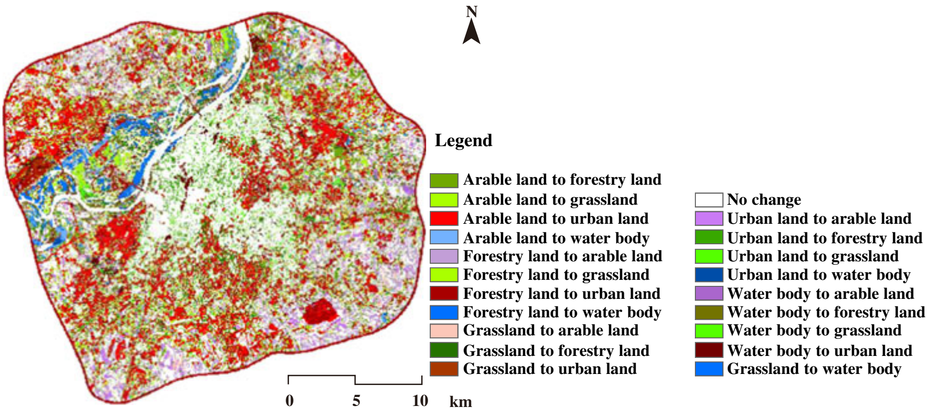


**Fig. 4** Land use change in the study area from 1976 to 2010

## Variation in land use/cover and habitat types along the urbanization gradient

As shown in Figs. 5 and 6, the current land use structure and the structure of ruderal habitats in different zones show obvious spatial disparities. Compared with Z1 and Z2, the proportion of urban land in Z3 is much less, and the proportions of grassland and arable land are greater. In contrast with Z3, where arable land accounts for 29.7 % of land cover, the proportion of arable land is only 0.3 % in Z1 and 1.2 % in Z2. The proportion of forest land in Z3 is higher than in Z2 and lower than in Z1. Additionally, 'water body' is only found in Z3. Moving from Z1 to Z3, the percentage of road gap ruderal habitat decreases, while the percentages of soil abandoned land and forest gap ruderal habitats increase. The percentages of road gap and gravel abandoned land ruderal habitats decrease from Z1 to Z2, and then increase from Z2 to Z3. From Z1 to Z2, the percentages of lawn and shrub-grassland gap ruderal habitats increase, while from Z2 to Z3, they decrease. Additionally, wetland and arable land ruderal habitats are almost exclusively found in Z3.

**Table 1** The land use converting matrix in the study area from 1976 to 2010 (km$^2$)

| Land use From 1976 | To 2010 | | | | | Total 1976 |
|---|---|---|---|---|---|---|
| | Urban land | Water body | Grassland | Arable land | Forestry land | |
| Urban land | 98.1 | 2.0 | 19.7 | 14.3 | 13.8 | 148.0 |
| Water body | 7.4 | 17.6 | 2.0 | 3.0 | 5.0 | 34.9 |
| Grassland | 19.2 | 5.2 | 9.6 | 15.0 | 10.2 | 59.1 |
| Arable land | 84.9 | 6.4 | 34.7 | 79.5 | 29.4 | 234.8 |
| Forestry land | 39.3 | 4.5 | 17.3 | 37.3 | 16.5 | 114.9 |
| Total 2010 | 248.8 | 35.6 | 83.2 | 149.0 | 75.0 | 591.7 |

The rows denoted the land use form $i$ in 1976. The ranks denoted the land use form $j$ in 2010. $A_{ij}$ was the area of the land use form that was converted from $i$ in 1976 to $j$ in 2010. The summation of rows and ranks denoted the total area of each land use form in 2010 and 1976, respectively

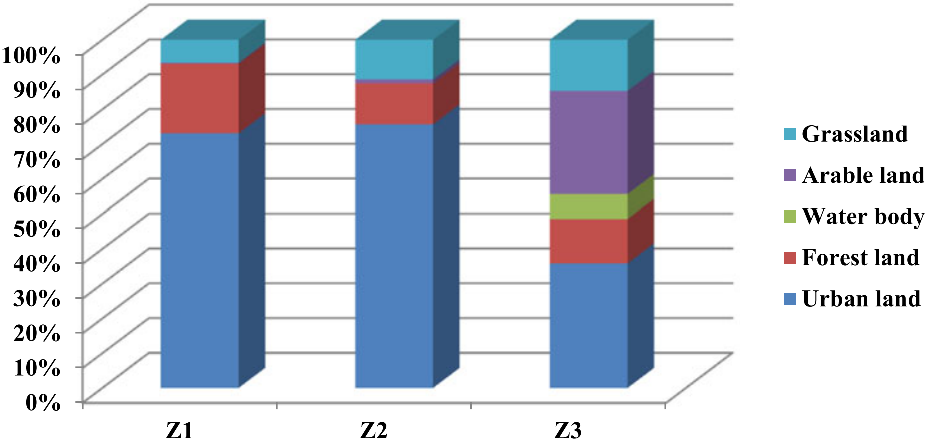


**Fig. 5** Structure of land use along the urbanization gradient

Current situation and the changes of ruderal floristic composition

*Dynamic change in species composition*

In our present field survey in 2010–2011, we recorded 175 ruderal species, belonging to 38 families and 128 genera. Cluster analysis grouped the 175 species into four ecological groups, i.e. widely distributed ruderal, Z1 ruderal, Z2 ruderal and Z3 ruderal (Table 2). As shown in Table 2, the four ecological groups of ruderal species exhibited obvious differences across the urbanization gradient. Widely distributed ruderal species accounted for 42.1 % of the total number of species and had the largest number of species in the study area, and they were dispersed across various habitats, including shrub-grassland gap, road gap, forest gap,

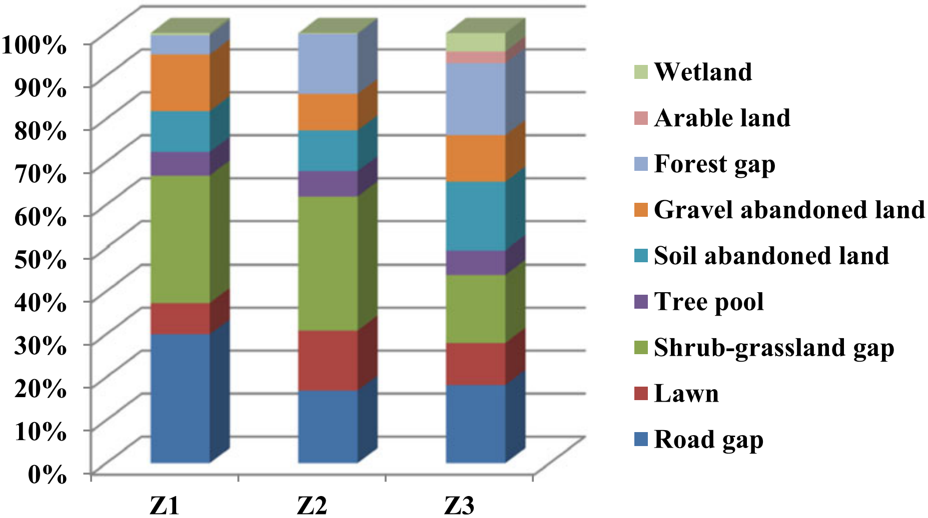


**Fig. 6** Structure of habitat types along the urbanization gradient

**Table 2** Characteristics of ecological groups for species

| Items | Widely distributed ruderal | Z1 ruderal | Z2 ruderal | Z3 ruderal |
|---|---|---|---|---|
| Number | 74 | 14 | 41 | 47 |
| Distribution area | Z1, Z2 and Z3 | Mainly in Z1, occasionally in Z2 or Z3 | Mainly in Z2, occasionally in Z3 | Only in Z3 |
| Proportion of life form (%) P/S/W | 39.2/51.3/9.5 | 7.2/71.4/21.4 | 43.9/48.8/7.3 | 57.4/36.2/6.4 |
| Proportion of areal type (%) T/T | 31.6/68.4 | 61.5/38.4 | 19.2/80.8 | 9.8/90.2 |
| Proportion of ecotype (%) A/H/M/X | 0/16.2/73.0/10.8 | 0/7.1/78.6/14.3 | 2.4/36.6/51.2/9.8 | 0/23.4/59.6/17.0 |

*P/S/W* perennial ruderal/summer annual ruderal/winter annual ruderal; *T/T* tropical ruderal/temperate ruderal; *A/H/M/X* aquatic ruderal/hygrophytic ruderal/mesic ruderal/xeric ruderal

abandoned land, lawn, tree pool, wetland and arable land. Moreover, there were 47 Z3 ruderal species, 41 Z2 ruderal species and 14 Z1 ruderal species.

In 1955, there were 611 species; however, by 2011, 436 (or 71.4 %) of these species had disappeared (Table 3). As shown in Table 3, Ruderal vegetation decreased significantly at both the family and genus levels. The number of ruderal families fell from 82 in 1955 to 38 in 2010–2011, and the number of ruderal genera fell from 311 in 1955 to 128 in 2010–2011. There were 36 remaining, 46 disappeared and two emerging ruderal families. Almost every remaining ruderal family lost a number of species. Moreover, the top five ruderal families changed from Gramineae, Compositae, Cyperaceae, Polygonaceae and Ranunculaceae in 1955 to Compositae, Gramineae, Leguminosae, Rosaceae and Labiatae in 2010–2011. The results indicated that the number of Gramineae, Cyperaceae and Polygonaceae species decreased significantly. Apart from Liliaceae and Potamogetonaceae, which both had a large number of species, most of the disappeared families had only one genus and one species. The emerging families belonged to Nyctaginaceae and Oxalidaceae, each of which were alien naturalized plants and had only one species.

As shown in Table 4, 499 species disappeared, 112 remaining and 64 were emerging over the past half century. The ruderal habitat for ruderal species changed significantly over the study period. Most of the disappeared species lived in moist meadows, waterfront of river or lake, water, wetland, hillside forest, arable land and other moist habitats. In contrast, most of the remaining species were found in dry and high interferential habitats, such as sunny abandoned land, road gap, grassland, forest gap, and arable land. The emerging species mainly occurred on abandoned land, shrub-grassland gap, tree pool and other habitats frequented by humans. Moreover, some of the disappeared species had medicinal or edible value. A proportion of the remaining species were more resistant to stress, or were widely distributed. Some escaping, alien, ornamental and edible species belong to the emerging species group.

*Dynamic change in life form*

Summer annual and perennial types dominated the life form of ruderal species in 2010–2011(Table 4). As shown in Table 2, along the urbanization gradient, summer annual accounted for 50.0 % of the total number of widely distributed ruderal species, and from

**Table 3** Dynamic change in number of family, genus and species of ruderal

| | Number | Family | Genus/Species | | Number | Family | Genus/Species | |
|---|---|---|---|---|---|---|---|---|
| | | | 1955* | 2010–2011 | | | 1955* | 2010–2011 |
| Remaining family | 1 | Gramineae | 46/88 | 14/16 | 19 | Asclepiadaceae | 2/5 | 1/1 |
| | 2 | Compositae | 43/81 | 23/36 | 20 | Malvaceae | 3/4 | 4/4 |
| | 3 | Cyperaceae | 7/42 | 2/2 | 21 | Urticaceae | 2/4 | 2/3 |
| | 4 | Polygonaceae | 4/28 | 3/9 | 22 | Boraginaceae | 4/4 | 2/2 |
| | 5 | Ranunculaceae | 12/24 | 3/3 | 23 | Typhaceae | 1/4 | 1/1 |
| | 6 | Leguminosae | 11/24 | 8/13 | 24 | Papaveraceae | 2/3 | 3/3 |
| | 7 | Rosaceae | 5/22 | 5/10 | 25 | Amaranthaceae | 1/3 | 1/2 |
| | 8 | Labiatae | 15/20 | 8/10 | 26 | Equisetaceae | 1/3 | 1/1 |
| | 9 | Brassicaceae | 15/19 | 7/7 | 27 | Crassulaceae | 1/2 | 1/2 |
| | 10 | Umbelliferae | 13/18 | 4/4 | 28 | Onagraceae | 2/2 | 1/1 |
| | 11 | Zygophyllaceae | 7/17 | 4/8 | 29 | Portulacaceae | 1/1 | 1/1 |
| | 12 | Caryophyllaceae | 10/17 | 3/3 | 30 | Commelinaceae | 1/1 | 1/1 |
| | 13 | Scrophulariaceae | 11/16 | 3/3 | 31 | Menispermaceae | 1/1 | 1/1 |
| | 14 | Convolvulaceae | 5/10 | 2/2 | 32 | Plantaginaceae | 1/3 | 1/4 |
| | 15 | Violaceae | 1/8 | 1/2 | 33 | Cucurbitaceae | 2/2 | 2/3 |
| | 16 | Iridaceae | 1/8 | 1/1 | 34 | Moraceae | 1/1 | 2/2 |
| | 17 | Euphorbiaceae | 2/6 | 2/2 | 35 | Geraniaceae | 2/4 | 2/3 |
| | 18 | Rubiaceae | 2/5 | 2/2 | 36 | Solanaceae | 3/3 | 4/5 |
| Disappeared family | 37 | Liliaceae | 10/23 | - | 60 | Chloranthaceae | 1/1 | - |
| | 38 | Potamogetonaceae | 1/10 | - | 61 | Plumbaginaceae | 1/1 | - |
| | 39 | Primulaceae | 4/7 | - | 62 | Lentibulariaceae | 1/1 | - |
| | 40 | Campanulaceae | 4/5 | - | 63 | Ophioglossaceae | 1/1 | - |
| | 41 | Najadaceae | 2/4 | - | 64 | Vitaceae | 1/1 | - |
| | 42 | Alismataceae | 2/4 | - | 65 | Lythraceae | 1/1 | - |
| | 43 | Saxifragaceae | 3/3 | - | 66 | Onocleaceae | 1/1 | - |
| | 44 | Nymphaeaceae | 3/3 | - | 67 | Thymelaeaceae | 1/1 | - |
| | 45 | Lemnaceae | 2/3 | - | 68 | Hippuridaceae | 1/1 | - |
| | 46 | Trapaceae | 1/3 | - | 69 | Paeoniaceae | 1/1 | - |
| | 47 | Haloragaceae | 1/3 | - | 70 | Dioscoreaceae | 1/1 | - |
| | 48 | Valerianaceae | 2/2 | - | 71 | Hydrocharitaceae | 1/1 | - |
| | 49 | Gentianaceae | 2/2 | - | 72 | Callitrichaceae | 1/1 | - |
| | 50 | Menyanthaceae | 2/2 | - | 73 | Juncaginaceae | 1/1 | - |
| | 51 | Juncaceae | 1/2 | - | 74 | Santalaceae | 1/1 | - |
| | 52 | Orobanchaceae | 1/2 | - | 75 | Guttiferae | 1/1 | - |
| | 53 | Balsaminaceae | 1/1 | - | 76 | Araceae | 1/1 | - |
| | 54 | Sparganiaceae | 1/1 | - | 77 | Adoxaceae | 1/1 | - |
| | 55 | Pedaliaceae | 1/1 | - | 78 | Linaceae | 1/1 | - |
| | 56 | Butomaceae | 1/1 | - | 79 | Pontederiaceae | 1/1 | - |
| | 57 | Zygophyllaceae | 1/1 | - | 80 | Polygalaceae | 1/1 | - |
| | 58 | Ceratophyllaceae | 1/1 | - | 81 | Rutaceae | 1/1 | - |
| | 59 | Pteridiaceae | 1/1 | - | 82 | Bignoniaceae | 1/1 | - |

**Table 3** (continued)

| | Number | Family | Genus/Species | | Number | Family | Genus/Species | |
|---|---|---|---|---|---|---|---|---|
| | | | 1955* | 2010–2011 | | | 1955* | 2010–2011 |
| Emerging family | 83 | Nyctaginaceae | - | 1/1 | 84 | Oxalidaceae | - | 1/1 |

- existence; * data in 1955, derived from the book of Index Florae Harbinensis (Baranov et al. 1955)

Z3 ruderal to Z1 ruderal, the ruderal life form changed from perennial-based (Z1) to summer annual and perennial-based (Z2) and to summer annual-based (Z3). The results showed that the proportion of perennial ruderal species decreased (by 50.2 %), and the proportion of summer annual ruderal and winter annual ruderal species increased (by 35.2 % and 15.0 %, respectively) from Z3 to Z1.

As shown in Table 4, there were obvious decreases in many of the perennial ruderal species over the past half century. Results suggest that the dominant ruderal life form changed from perennial-based to summer annual and perennial-based over this time period, such that up to 75 % of the disappeared ruderal species were perennial species. The proportions of perennial ruderal and summer annual ruderal to the remaining ruderal species and emerging ruderal species were both the same. Additionally, the proportions of winter annual ruderal species to the remaining ruderal species and emerging ruderal species were greater than the disappeared winter annual ruderal species at 2.6 % and 5.3 %, respectively, which reflects an increasing occurrence of winter annual species over the past half century.

*Dynamic change in areal type*

Temperate types dominated the areal type of ruderal species in 2010–2011 (Table 4). As shown in Table 2, along the urbanization gradient, temperate ruderal species accounted for 68.4 % of the total number of widely distributed ruderal species. Additionally, the proportion of tropical species increased (by 51.8 %), and the proportion of temperate species decreased (by 51.8 %), from Z3 to Z1 at the same time.

The proportion of tropical ruderal species decreased (by 13.5 %), and that of temperate ruderal species increased (by 13.5 %) over the past half century (Table 4). Compared with the temperate-based disappeared species, the proportion of temperate ruderal to both the remaining species and emerging species decreased (by 16.9 % and 15.8 %, respectively).

*Dynamic change in ecotype*

Mesic types dominated the ecotype of ruderal species in 2010–2011 (Table 4). As shown in Table 2, along the urbanization gradient, mesic ruderal species accounted for 73.0 % of the total number of widely distributed ruderal species, and dominated Z1, Z2 and Z3. The proportion of xeric ruderal decreased by 7.2 % from Z3 to Z2, and then increased by 4.5 % from Z2 to Z1.

As shown in Table 4, the smallest ecotype was xeric ruderal that was accounted for 4.6 % of the total number of ruderal species in 1955, but by 2011, had changed to aquatic ruderal that was accounted for 0.6 %. Moreover, the proportion of aquatic ruderal and hygrophytic ruderal species clearly decreased over the studied half century. Compared with the

**Table 4** Changing characteristics of ruderal species diversity

| Items | 1955 | Disappeared species | Remaining species | Emerging species | 2010–2011 |
|---|---|---|---|---|---|
| Number | 611 | 499 | 112 | 64 | 175 |
| Proportion of life form (%) P/S/W | 69.2/23.2/7.5 | 75.0/17.8/7.2 | 43.8/48.2/9.8 | 40.6/46.9/12.5 | 42.3/47.4/10.3 |
| Proportion of areal type (%) T/T | 17.2/82.8 | 14.0/86.0 | 30.9/69.1 | 29.8/70.2 | 30.7/69.3 |
| Proportion of ecotype (%) A/H/M/X | 8.0/36.3/51.1/4.6 | 9.6/38.1/49.1/3.2 | 0.9/28.6/59.8/10.7 | 0/10.9/71.9/17.2 | 0.6/22.3/64.0/13.1 |
| Mainly habitat conditions | | Moist meadows, waterfront of river or lake, water, wetland, hillside forest, arable land | Sunny abandoned land, road gap, grassland, forest gap, arable land | Abandoned land, shrub-grassland gap, tree pool | |
| Application value and others | | Medicinal value, edible value | Higher stress resistance, widely distributed | Escaping species 35.9 %, alien species 46.9 %, ornamental value, edible value | |

*P/S/W* perennial ruderal/summer annual ruderal/winter annual ruderal; *T/T* tropical ruderal/temperate ruderal; *A/H/M/X* aquatic ruderal/hygrophytic ruderal/mesic ruderal/xeric ruderal disappeared ruderal, the proportion of hygrophytic ruderal to both the remaining and emerging ruderal species decreased (by 9.5 % and 27.2 %, respectively), while that of mesic and xeric ruderal species both increased at the same time.

## Discussion

### Ruderal species composition change and its causes

Rapid urbanization has brought dramatic changes to urban environments (Wang et al. 2008; Xia et al. 2011). Similar to previous studies (Zhang et al. 2010; Zhou et al. 2004), we have shown that the mean annual temperature in Harbin has increased over the past half century because of global warming and urbanization. The increase in the mean annual temperature was considered to relate with the decrease in temperate ruderal, and an increase in tropical ruderal species. It was also considered to relate with the emergence of thermophilic ruderal species, such as *Oenothera biennis* and *Eleusine indica*.

As part of the rapid urbanization process, the study area experienced dramatic land use change over the past 34 years, which has resulted in more artificial and unstable urban habitats. Moreover, the increased area of impervious surfaces with poor infiltration has resulted in dramatic changes in dry and wet urban habitats. For example, in the process of urban construction, much of the wetland, forest and arable land along the Songhua River was converted into artificial water bodies that were integrated into scenic spots or wetland parks, which require intensive and frequent management. Additionally, the construction of a dam in the lower reaches of Songhua River to supply landscape water increased the area of water body. Despite this extra area of water body, aquatic ruderal species struggled to survive because of human activities in water bodies. The decrease of natural water bodies and wetlands was considered with the extinction of a large number of aquatic and hygrophytic ruderal species, such as *Trapa manshurica* and *Coleanthus subtilis*. The extinction of hygrophytic ruderal has led to a decrease in Cyperaceae and Polygonaceae species. Most of the arable land ruderal species, such as *Alopecurus pratensis* and *Alopecurus aequalis*, went extinct because of the dramatic decrease in, and intensive cultivation of, arable land. Although grassland increased, it was no longer suitable for the native grassland ruderal species because, by 2010, most of the grassland had been converted from urban land and forest land to artificial lawn, composed of species such as *Eragrostiella lolioides* and *Festuca rubra*. Therefore, the number of Gramineae species decreased significantly got the similar results with the extinction of ruderal species in grassland.

Urbanization is the result of human disturbance. Because of the high intensity and high frequency of human disturbance, urban habitats have become more unstable, making it difficult for ruderal species to follow the natural succession sequence from annual to perennial species (Chen 2005; Wang 2006; Li 2009). The dominant ruderal life form in the study area changed from perennial-based to summer annual and perennial-based because of severe human disturbance of ruderal habitats. A large number of perennial ruderal species, such as *Clinopodium chinense* and *Phlomis tuberosa*, which previously only grew in stable habitats, are now extinct because of the increase in unstable habitat. Additionally, over time, as living standards improved, people started to pay more attention to the practical value of wild ruderal vegetation, and excessive picking was considered to relate with the extinction of many of the wild edible ruderal (for example, *Hemerocallis citrine* and *Allium macrostemon*) and medicinal ruderal species (for example, *Lysimachia davurica* and *Orobanche pycnostachya*).

Additionally, as part of the urbanization process, some new habitat types have been created in the study area, including temporary bare land, from urban construction, and artificial lawn, characterized by frequent trampling and mowing. The temporary bare land includes soil and gravel abandoned land, which are rich in N and P. Alien pioneer ruderal species, such as *Chenopodium hybridum* and *Messerschmidia sibirica*, have become established on this land. A large number of trampling and mowing resistant ruderal species found in artificial lawn, such as *Polygonum aviculare* and *Plantago media*, have survived the impacts of human activities. Moreover, some new species, such as *Viola philippica* and *Potentilla bifurca*, have emerged.

Urbanization is occurring at a rapid pace throughout the world, especially in China (Houghton 1994; Hepinstall-Cymerman et al. 2013). Moreover, China is searching for novel ways to conserve urban biodiversity (Normile 2008), i.e. urban re-naturalization. On the one hand, the construction of urban forest was considered to relate with the emergence of a large number of plantations in urban areas. While urban forest is suitable habitat for forest ruderal growth, because of human activities, only ruderal species that are resistant to trampling and mowing, such as *Silene aprica* and *Agrimonia pilosa*, are able to grow. On the other hand, many ornamental and edible alien species, such as *Saponaria officinalis* and *Orychophragmus violaceus,* have been introduced into the urban area, and these have become ruderal during urban landscape development. Although the ruderal species that have evolved because of urban landscape construction have improved urban biodiversity to some extent, it has been an artificial success. That said, the emergence of ruderal species during the construction of urban forest can definitely improve urban biodiversity.

The increased human disturbance from suburban to urban that accompanies the spread of urbanization results in the formation of a complex environment gradient (Mooney and Hobbs 2000). In this study, typical urban habitats for ruderal species changed from moist and low interferential habitats to dry and high interferential habitats. Over the study period, habitat heterogeneity has appeared in the urban area of Harbin. The integration and reduction of land use types has changed the distribution of ruderal species diversity. From Z3 to Z1, the number of land use types decreased and the proportion of urban land increased. The high proportion of impervious surfaces has resulted in a decreased number of suitable ruderal habitats, such that we recorded most ruderal species in abandoned land, road gap and shrub-grassland gap habitats. Additionally, as urbanization has increased, the ruderal life form has changed from perennial-based (Z3) to summer annual and perennial-based (Z2) and to summer annual-based (Z1) because of the increased impact of human disturbance and management.

## Adaptive strategies of ruderal vegetation to urbanization

Rapid urbanization has brought dramatic changes to both the urban environment and urban land use (Currit and Easterling 2009), and has resulted in changes in ruderal species diversity. Ruderal vegetation is likely to respond differently to the various urban habitats (Alberti 2005; Trammell and Bassett 2012).

Annual ruderal species have adopted a short life cycle to help them adapt to habitats with frequent and severe human disturbance, such that the proportion of annual ruderal species has increased dramatically over the past half century. With the exception of widely distributed ruderal species, annual ruderal species increased gradually from Z3 ruderal to Z1 ruderal, with annual ruderal accounting for up to 92.8 % of Z1 ruderal. Ruderal species cannot evolve from annual to perennial because of the high frequency of human disturbance. However, annual ruderal species can complete their life cycle in a short time to reduce the impact of human activities. For example, to survive trampling and maintain their propagation capability, most annual ruderal species in Harbin are short, and some of the winter annual ruderal species have rosette plants, similar to what was found in previous studies (Ou and Yu 1994; Tian et al. 2008). Additionally, the proportion of winter ruderal species increased slightly from Z3 to Z1, which is consistent with previous studies in central European, Japan, Malaysia and Shanghai (Lososova et al. 2006; Ohtsuka et al. 1993; Ohtsuka 1999; Tian 2011). The proportion of winter ruderal also increased from 1955 to 2011, suggesting that winter annual ruderal species might be more adaptable to special urban habitats.

The widely distributed ruderal species adapted universally to the various urban various habitats. Their seeds have a longer life span, can adapt to deteriorated habitats and can maintain their vitality for many years while buried in soil. They can also be dispersed by, among other methods, wind, water and birds. These ruderal species have chosen an extreme survival strategy in high stress habitats, and have germinated when the habitat was suitable. Widely distributed ruderal species that are highly adaptable may be more able to adapt to urban heterogeneous habitats than other less adaptable species. We observed that some of the widely distributed ruderal species, for example *Polygonum aviculare* and *Chenopodium glaucum*, were more adaptable and flexible than others, while other species, for example *Solanum nigrum* and *Chenopodium album*, were more competitive for space.

To adapt to the unstable habitats, ruderal species are characterized by a short life cycle, relatively fast growth rates and high seed yields. Moreover, different ruderal species have chosen different life cycle strategies. We describe two such strategies here.

(1) The CR-strategy (competitive ruderal strategy) has been chosen by ruderal species in habitats with rich resources, such as soil abandoned land and areas with a low rate of urbanization. These ruderal species are highly competitive and able to spread rapidly. They allocate most of their nutrient supply to growth and reproduction. Some of the remaining species, for example *Solanum nigrum* and *Chenopodium album*, have adopted the CR-strategy over the past 56 years.
(2) The second strategy is the SR-strategy (stress-tolerant ruderal strategy), which is chosen by ruderal species in resource-poor habitats, such as gravel abandoned land and road gap. This kind of ruderal species can tolerate serious resource stress. They allocate their main nutrient to survival and reproduction, and, to survive, they shorten their height. Most species in this group are annuals and short-lived perennials, and are highly stress resistant, such as *Polygonum aviculare* and *Chenopodium glaucum*.

## Suggestions for the government

Conservationists have long debated how best to preserve urban biodiversity (Charles and Godfray 2011). As an urban biodiversity filler (Cai et al. 2012), ruderal vegetation plays an important role in urban biodiversity conservation (Zhang et al. 2009) and has a certain degree of practical value.

Rapid urbanization has had a tremendous impact on ruderal species diversity in Harbin over the past half century. If the present trend continues, the threat to ruderal species diversity will perhaps be even greater in the future. Therefore, the Harbin government should act on the following recommendations to improve urban biodiversity conservation and management: (a) We recommend that human disturbance to ruderal vegetation should be minimized, that the provision of living space for ruderal growth be prioritized and that the contribution of ruderal vegetation to urban biodiversity should be acknowledged. With ruderal species, there is no longer a need to weed in the water conservation areas. (b) It is necessary to develop the application value of ruderal species. We should select native species, which are vigorous and provide good landscape effects, as the pioneer species to increase the urban greening species resource, to enrich the green landscapes and to achieve restoration and reconstruction of vegetation in the worst urban habitats.

Harbin is experiencing rapid urbanization, and the impact of urbanization on ruderal species diversity might be more serious in the future than has already been observed. The results of this present study highlight the importance of carrying out long-term research on the impacts of rapid urbanization on ruderal vegetation.

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