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Naturalization of alien plants in China

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Abstract Naturalization (the establishment of a self-sustaining population for at least a decade) is a fundamental precondition for plant invasion and so compiling a complete inventory of naturalized alien species is necessary for predicting and hence preventing such invasion. However, nationwide information on naturalized plants in China is still lacking. We compiled a nationwide list of the naturalized plant species of China, based on various literature reports. The list comprised a total of 861 naturalized plant species belonging to 110 families and 465 genera. The three most dominant families were *Compositae*, *Poaceae*, and *Leguminosae*, accounting for 16, 13 and 12% of naturalized plants, respectively. Among genera, *Euphorbia* and *Solanum* had the most naturalized species, followed by *Ipomoea*, *Amaranthus*, *Oenothera*, and *Trifolium*. Over half of all aliens were of American origin (52%), followed by those with European (14%) and Asian (13%) origins. Annuals and perennial herbs were prevalent among naturalized species; comparison to other studies suggests however that the invasive potential is higher among plants with longer life cycles than those of annuals. The taxonomic pattern of plant naturalization in China is similar to patterns worldwide. However, the low proportion of naturalized plants within the Chinese flora overall suggests that the potential for plant invasions in China may be high. Therefore, greater attention should be focused on naturalization of alien plants in China, especially concerning species of dominant families or genera, and those with a perennial life cycle.

Keywords Invasion · Life form · Naturalization · Taxonomic pattern

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Introduction

Biological invasions by alien species are widely recognized as a significant component of human-caused global environmental change. Invasive alien plant species may profoundly alter ecosystem structure, resulting in significant losses in the economy, and in the biological diversity and function of invaded ecosystems, and thus are of great concern to both ecologists and economists (Elton 1958; Lonsdale 1999; Pimentel et al. 2000; Meyerson and Mooney 2007).

The stages in the invasion process of alien plants are complex and the processes represent a continuum. Naturalization is a fundamental precondition for plant invasion. The naturalization process of alien plants introduced intentionally or unintentionally occurs when abiotic and biotic barriers to survival and reproduction are overcome. Naturalized plants may become invasive in new habitats only when they produce adequate reproductive off-spring (Richardson et al. 2000; Pyšek et al. 2004). Compilation of comprehensive lists of the naturalized species list for a given country, and comparative studies of naturalized floras in different regions, have proved to be a useful approach to understanding taxonomic patterns of plant invasion (Pyšek et al. 2004; Khuroo et al. 2007) and are the first steps towards developing management strategies for invasive species.

China is the world's third largest country with a total area of 9.6 million km² and encompassing a wide range of habitats and environmental conditions (Xie et al. 2001). The estimated annual economic loss in China due to invasive alien species may amount to US\$ 15 billion (Xu et al. 2006a). The problem of invasive alien species in China has been discussed by a number of authors with emphasis on harmful invasive plants (e.g., Ding and Wang 1998; Qiang and Cao 2000; Li and Xie 2002; Liu et al. 2005; Xu et al. 2006b; Liu et al. 2006; Ding et al. 2008; Weber et al. 2008; Huang et al. 2009; Feng and Zhu 2010). A number of regional lists of naturalized plants have been compiled, e.g., for Shandong (Wu et al. 2006), Guangzhou (Yan et al. 2007), Hong Kong (Corlett 1992, Ng and Corlett 2002), Macau (Wang et al. 2004), and Taiwan (Wu et al. 2004a, b, 2010b). Most recently, a list of 420 naturalized plant species occurring in mainland China was compiled by Wu et al. (2010a). This provided an important advance, while nationwide documentation of naturalized plants in China is still lacking.

Considering that the naturalized floras of many countries or continents have been well documented, e.g., Europe (Weber 1997; Lambdon et al. 2008), Mexico (Villaseñor and Espinosa-Garcia 2004), Kashmir Himalaya (Khuroo et al. 2007), North Africa (Vilà et al. 1999), Austria (Rabitsch and Essl 2006), and Singapore (Corlett 1988), comprehensive documentation of naturalized alien species in China therefore stands to provide an important data set for comparative studies of alien floras, and offer new insights to our understanding of global patterns of plant invasions. In this light, our main objective in the present study is to compile a database of naturalized plants in China. Based on this compilation, we then address the four specific questions: (1) What is the current prevalence of naturalized plants in China? (2) Is there a taxonomic pattern? (3) Where did these species originate? and (4) Are there life form and habit characters associated with plant invasion? We hope that this effort will contribute towards offering insightful perspectives and information for further regional or global studies of plant invasion.

Methods

Definition

In both English and Chinese literature, the concepts associated with terms “invasion”, “naturalization”, “alien” species, and “exotic” species are often confused. This confusion may lead to over- or under-estimation of the real level of invasion or naturalization in a given region, and is also an obstacle for comparative research on the spread of alien plants around the world. For the purpose of this study, the terms used in the present paper are defined here strictly according to concepts suggested by Richardson et al. (2000) and Pyšek et al. (2004). Alien plants in China are all those which have their origins outside China and were introduced intentionally or accidentally. Naturalized plants are alien plants that sustain self-replacing populations for at least 10 years without direct intervention by people and which are capable of independent growth. Invasive plants are a subset of naturalized plants which produce reproductive offspring, and have spread beyond their area of introduction. The term “invasive” used here is defined without any inference to environmental or economic impact.

Catalogue of naturalized species

We compiled a nationwide list of the current naturalized flora of China (Appendix S1), based on the list of 233 invasive plant species in China released by the Institute of Plant Protection (IPP), Chinese Academy of Agricultural Sciences (CAAS) (2008) (<http://www.agripests.cn>), regional lists of invasive and naturalized plant species, and various other publications released before October 2010 (references listed in Appendix S1). Only plant species with foreign origins were considered as naturalized, and so a number of species that have been considered by some authors as naturalized in some regions of China but native to other regions of the country were not included. For example, many species native to south China were identified as naturalized and invasive species in Hong Kong or Taiwan; we deleted these in the present list. The synonyms of some species were corrected to their accepted names according to the ‘Catalogue of Life, China, 2009 Annual Checklist’ (http://data.sp2000.cn/2009_cnode_c/search.php), or the ‘Flora of China’ (1959–2002) (Editorial Board for Flora of China). The naturalized status, origins, life forms of these species were extracted from these references, and were further corrected one by one following the ‘Flora of China’ or various provincial floras.

Data analysis

We calculated the number and proportions of naturalized species per family and genus in China and the world; we further compared the ratios with equivalent global patterns using linear correlation analysis. We also calculated the proportions of species in each category of origin, life form. Because information on the native distribution of species provided in different references is not always consistent, we grouped species by broad categories, i.e., “Africa”, “America”, “Asia”, “Europe” and “Oceania”. If a species occurred in more than one area, we placed it in the one where it occurred most frequently; meanwhile, the details on species’ distributions are presented in Appendix S1. The proportion of climbing plants (vines and lianas) in the total naturalized flora was also analyzed because these are often the most harmful invasive plants in south China (Hu et al. 2010).

Results

Taxonomic diversity

A total of 861 naturalized plant species belonging to 110 families and 465 genera were recorded. They represent about 2.3% of the approximately 37,000 vascular plant flora of China (Catalogue of Life, China, 2009 Annual Checklist; Table 1; Appendix S1). Among these species, 79% (681) were dicotyledons, 20% (168) were monocotyledons, nine species were pteridophytes and three were gymnosperms. Three families, *Compositae*, *Poaceae*, and *Leguminosae*, have more than 100 naturalized species in China and account for 16, 13 and 12% of the total naturalized plants in the country, respectively (Table 2, Appendix S2). Another five families including *Solanaceae*, *Cruciferae*, *Euphorbiaceae*, *Amaranthaceae* and *Convolvulaceae* had more than 26 naturalized plants (>3% of the total naturalized species in China) each, while about 42% of the families (46) contributed only one species to the naturalized flora. This taxonomic pattern of plant invasion in China is highly similar (Fig. 1, $r = 0.79$, $P < 0.0001$) to the worldwide pattern summarized by Pyšek (1998).

Six genera had more than 10 naturalized species: *Euphorbia* (*Euphorbiaceae*) and *Solanum* (*Solanaceae*) have the most naturalized species (18), followed by *Ipomoea* (*Convolvulaceae*), *Amaranthus* (*Amaranthaceae*), *Oenothera* (*Onagraceae*) and *Trifolium* (*Leguminosae*) (Table 3). Each of another 22 important naturalized genera hold more than 5 naturalized species, while about 50% of the genera are represented by a single naturalized species (Appendix S1).

Geographic origin

More than half of the naturalized alien plant species of China were of American origins (52%), followed by those with European (14%) and Asian (13%) origins. Africa was also an important origin of the naturalized plant species (74 species, 9%), while less than 20 naturalized plant species from the Mediterranean, the Pantropics, and Oceania, each of them accounted for <2% of the total naturalized plant species in China (Fig. 2). The information on the native distributions of about 2% of the naturalized species was not consistent, or the origins were unclear.

Life form

The life forms of the naturalized plants were characterized by a prevalence of annuals and perennial herbs (Fig. 3). Herbs accounted for about 82% (including vines), while woody

Table 1 Taxonomic composition of the naturalized flora of China

Plant group	Number of families	Number of genus	Number of species	% of (species pool of China)
Dicotyledons	83	368	681	2.5 (27,752)
Monocotyledons	20	90	168	2.5 (6,624)
Gymnosperms	2	2	3	0.9 (316)
Pteridophytes	5	5	9	0.4 (2,433)
Total	110	465	861	2.3 (37,125)

The species pool of China based on Catalogue of Life, China, 2009 Annual Checklist

Table 2 Taxonomic diversity in the families with more than five naturalized plant species in China

Family	Species	Genera	China (%)	World (%)
Compositae	134	76	5.2	0.6
Poaceae	109	50	5.1	1.1
Leguminosae	106	47	5.3	0.6
Solanaceae	38	11	32	1.3
Cruciferae	35	18	7.4	1.1
Euphorbiaceae	29	9	6.8	0.4
Amaranthaceae	27	7	49	3.6
Convolvulaceae	26	7	17	1.6
Onagraceae	18	4	24	2.8
Rubiaceae	16	11	2.0	0.2
Scrophulariaceae	16	10	1.9	0.3
Malvaceae	14	9	12	0.8
Caryophyllaceae	13	9	2.7	0.6
Labiatae	13	8	1.3	0.2
Acanthaceae	11	8	3.5	0.3
Cactaceae	9	5	100	0.6
Cyperaceae	9	5	0.9	0.2
Umbelliferae	9	8	1.3	0.3
Verbenaceae	9	6	4.0	0.9
Apocynaceae	8	7	5.4	0.4
Agavaceae	7	1	100	3.3
Cucurbitaceae	7	6	3.4	0.9
Polygonaceae	7	6	2.5	0.6
Amaryllidaceae	6	4	14	0.8
Araceae	6	5	2.4	0.2
Boraginaceae	6	4	1.8	0.3
Chenopodiaceae	6	2	2.9	0.5
Iridaceae	6	3	8.1	0.4
Crassulaceae	5	4	1.8	0.5
Liliaceae	5	4	0.6	0.1
Lythraceae	5	4	10	0.8
Passifloraceae	5	1	20	0.9
Plantaginaceae	5	1	19	1.8
Ranunculaceae	5	1	0.4	0.2
Zingiberaceae	5	5	2.1	0.5

China (%) represents the number of naturalized species in each family in China: the total number of species in each family in China. Similarly, world (%) represents the number of naturalized species in each family in China: the total number of species in each family worldwide (Mabberley 1997)

plants (shrub and tree) comprised only 13% of the total naturalized plants, with semi-shrubs (herb/shrub) accounting for the remaining 4%. The total number of climbers amounted to 8% of the naturalized plants, with 6% vines and 2% lianas.

We compared the proportion of naturalized annual: perennial species in our dataset to the equivalent proportion in the datasets on invasive plant species (compiled by Weber et al. 2008) and on “major” invasive plant species (compiled by Liu et al. 2006). We found that the proportion of annual plant species decreased evidently when moving from naturalized through invasive to “major” invasive (Fig. 4).

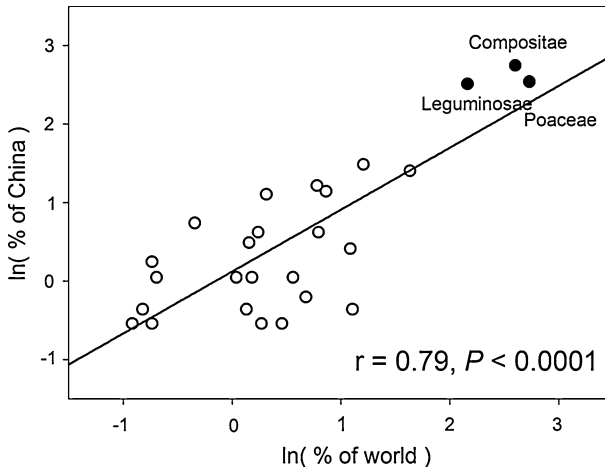


Fig. 1 The taxonomic pattern of plant naturalization in China compared to patterns worldwide. The proportion of naturalized plant species per family (for families with more than five naturalized plant species): total naturalized species compared between China and the average of 26 naturalized floras for elsewhere in the world determined by Pyšek (1998)

Discussion

Most previous studies of alien species in China have focused on spatial patterns, species composition and risk assessment of “harmful invasive plants”. However, the number of invasive plants in China reported in previous publications has varied widely, likely due to varying taxonomies, varying definitions of “invasive” and to incremental increases in knowledge. For example, Ding and Wang (1998) reported 58 invasive plants of China; 80 (Xiang et al. 2002); 90 (Li and Xie 2002), 108 (Qiang and Cao 2000), 126 (Liu et al. 2006), 188 (Xu et al. 2006b), and 270 (Weber et al. 2008). Weber and Li (2008) have suggested that a research priority for efficient invasive species management program in China is therefore to assemble standard information on the country’s naturalized species.

In the present study, the total number of recorded naturalized plant species was more than twice as many as that reported by Wu et al. (2010a). This increase in the total number of naturalized plants is likely due to a combination: (1) nationwide coverage (including not only mainland China, but also Hainan, Hong Kong, Macao, and Taiwan); (2) compilation of further relevant documents and literatures, especially the recently published regional floras and naturalized literatures; and (3) strict definition of “naturalized”, without any inference to environmental or economic impact. Nevertheless, the total number and the proportion of naturalized plants to the whole flora in China are still relatively low compared with other regions. For example, 1,780 naturalized alien plant species have been recorded in Europe (Lambdon et al. 2008), accounting for about 15% of the continent’s flora. The proportions of naturalized plant species in other northern-hemispheric regions are even higher, e.g. Ontario (Canada) 28% (Morton and Venn 1990), and California (USA) 18% (Hickman 1993). Only northern Africa has a similarly low proportion, at 1.8–4.9% in different regions (Vilà et al. 1999).

Two factors might explain the relatively low proportion of naturalized plants in China. First, very likely, we underestimate the naturalized flora, due to shortfalls in both knowledge and available information. We hope that the present compilation could

Table 3 The dominant genera (with five or more species) of naturalized species in China

Genera	Species	China (%)	World (%)
<i>Euphorbia</i>	18	23	0.9
<i>Solanum</i>	18	42	1.1
<i>Ipomoea</i>	17	50	2.6
<i>Amaranthus</i>	14	88	23
<i>Oenothera</i>	12	100	9.7
<i>Trifolium</i>	11	73	4.6
<i>Crotalaria</i>	8	15	1.3
<i>Lolium</i>	8	100	100
<i>Paspalum</i>	8	44	2.4
<i>Agave</i>	7	100	7.0
<i>Setaria</i>	7	37	4.7
<i>Vicia</i>	7	12	5.0
<i>Alternanthera</i>	6	100	6.0
<i>Brassica</i>	6	25	17
<i>Lepidium</i>	6	38	4.3
<i>Senna</i>	6	67	1.7
<i>Veronica</i>	6	9.5	3.3
<i>Acacia</i>	5	19	0.4
<i>Bidens</i>	5	33	2.1
<i>Cassia</i>	5	33	17
<i>Cyperus</i>	5	9.4	1.7
<i>Mimosa</i>	5	100	1.0
<i>Opuntia</i>	5	100	2.5
<i>Passiflora</i>	5	24	1.2
<i>Pennisetum</i>	5	45	3.9
<i>Phyllanthus</i>	5	14	0.8
<i>Plantago</i>	5	19	1.9
<i>Ranunculus</i>	5	3.2	0.8

China (%) represents the number of naturalized species in each genus in China: the total number of species in each genus in China. Similarly, world (%) represents the number of naturalized species in each genus in China: the total number of species in each genus worldwide (Mabberley 1997)

stimulate initiation of compiling checklists of naturalized and invasive species in all provinces of China. Second, it is well recognized that naturalization and invasion of alien plants are greatly correlated with human activities (Meyerson and Mooney 2007). Although plant introductions in China have a long history (Xie et al. 2001), large-scale introduction of species from other continents is a rather recent phenomenon (Weber et al. 2008). It is also well documented that the patterns of plant naturalization/invasion are fundamentally linked with the intensity of international trade/tourism (Thuiller et al. 2005); and the frequency of trade/travel between China and other regions was very low before 1980, which was probably a main reason for the relatively low proportion of naturalized plants in China. However, China is currently undergoing a rapid economic development and increasing international trade, and as a consequence, plant invasions in China have intensified dramatically in recent decades (Lin et al. 2007), and more invasions are supposed to occur in near further (Weber and Li 2008).

The present comprehensive catalogue of naturalized plants in China elucidates the taxonomic pattern of plant invasion in China relative to the rest of the world. The three most prevalent naturalized families in China, *Compositae*, *Poaceae*, and *Leguminosae*, are

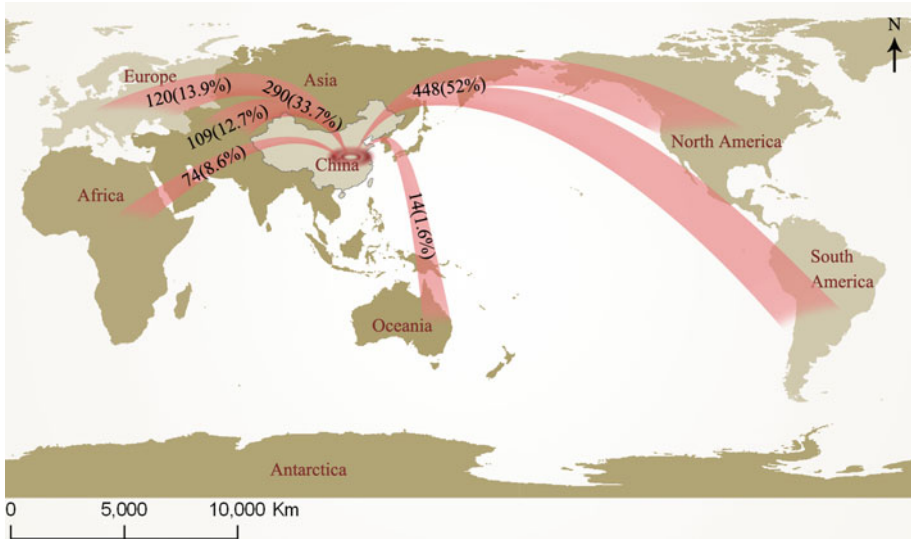


Fig. 2 Geographical origin of the naturalized plant species of China. The 33.7% Asian and European origins also includes 7.1% Eurasian and 1.7% Mediterranean origins. Besides these, Pantropics, Cosmopolitan and uncertain origins accounts for the rest 2, 0.7 and 1.4%, respectively

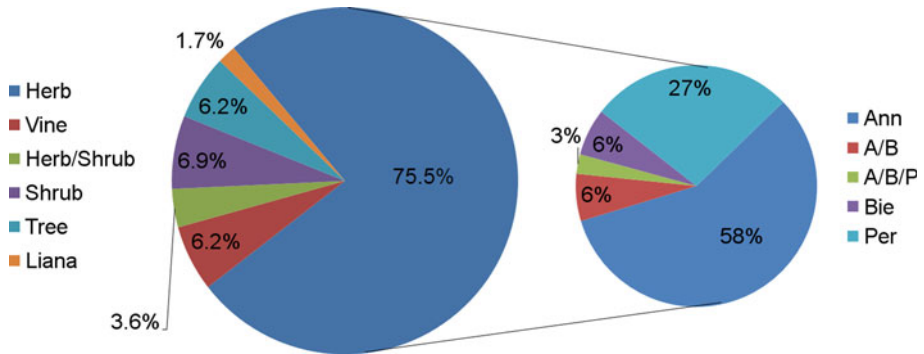


Fig. 3 Life form of the naturalized plant species in China. *Left*: life form of the naturalized plants; *Right*: life form of herbs. *Ann* annual, *Bie* biennial, *Per* perennial, *A/B* annual or biennial, *A/B/P* annual or biennial or perennial

also major contributors to the alien floras in many other regions of Asia (Corlett 1988; Wu et al. 2004a, b) and of the world (Hickman 1993; Weber and Li 2008). These families are among to the largest families worldwide (Daehler 1998; Douglas et al. 2009), and indeed, global family size has been shown to be a predictor for the number of alien plants in a flora (Hickman 1993; Weber 1997; Zerbe et al. 2004; Lambdon et al. 2008). The other five dominant families were also well represented in alien floras of Asia and of the world (Heywood 1989, 1993; Morton and Venn 1990; Khuroo et al. 2007). Some families, such as *Labiatae*, *Cucurbitaceae*, *Amaryllidaceae*, *Araceae*, were overrepresented in the naturalized flora of China compared with that for the world (Appendix S2) presumably due to their introduction into China as ornamentals, herbal medicines or vegetables.

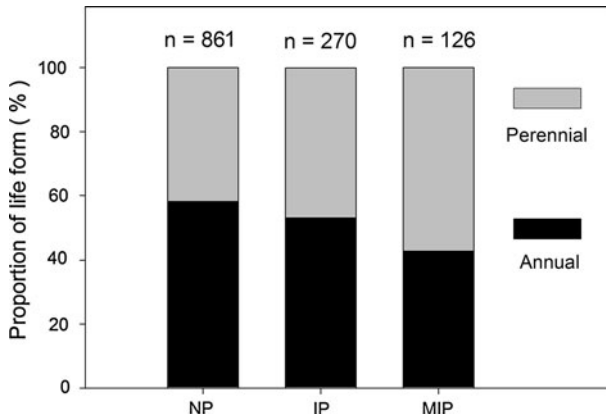


Fig. 4 Changes of proportion of life form during naturalization and invasion stages. Data of invasive plants are extracted from Weber et al. (2008), and data of major invasive plants are from Liu et al. (2006). *NP* naturalized plants, *IP* invasive plants, *MIP* major invasive plants. Annuals used here include annual or biennial herb and vein; perennials used here include perennial herb, herb/shrub, shrub, liana and tree

A total of 28 genera hold five or more naturalized plants, six of which hold ten or more; all of these are very species plant genera. The naturalized proportions of these and other genera in China were also remarkably high, for examples, 100% naturalization ratios for *Alternanthera*, *Agave*, *Lolium*, *Mimosa*, *Oenothera* and *Opuntia*, and over 50% for *Amaranthus*, *Ipomoea*, *Senna* and *Trifolium* (Table 3). Furthermore, according to the risk assessment conducted by Feng and Zhu (2010), these genera also contained approximately one-third of the most noxious invasive plants in China, such as *Alternanthera philoxeroides*, *Lolium temulentum*, *Ipomoea purpurea*, and *Solanum rostratum*. The naturalized species belonging to these genera should be monitored carefully, and further introduction of species belonging to these genera should be minimized.

The geographical origin of naturalized species may influence their invasiveness in new areas (Wu et al. 2004a, b; Arianoutsou et al. 2010). As in most naturalized floras, naturalized plant species in China originated from all continents. These data presented here are fairly consistent with previous analyses of the geographical origins of invasive plants in China (Liu et al. 2006; Xu et al. 2006b; Wu et al. 2010a), and in neighboring regions (Corlett 1988; Enomoto 1999; Koh et al. 2000). We can speculate as to two probable reasons for such a high proportion of American species in the alien flora of China (52%). First, this could be driven by the fact that naturalization success is increased with similarity of climate and biota: China and North America share a wide range of similar environments and related biota, which may render each region more susceptible to each other's immigrant species than species from elsewhere (Guo 1999, 2002). Second, commerce between the two regions has soared in the past few decades, which could have facilitated an upsurge in the transport of plant propagules from North America to China (Liu et al. 2006; Ding et al. 2008; Weber et al. 2008). On the other hand, China is potentially less prone to invasions by South African plants in the near future; since there is quite low exchange of trade and tourism between China and South Africa, although the climate of China is suitable for certain plants originating from South Africa (Liu et al. 2005; Thuiller et al. 2005).

The question of whether it is possible to determine a set of traits that predispose a species towards naturalization has been a central theme since the emergence of invasion ecology as a discrete field of study (Richardson and Pyšek 2006; Pyšek and Richardson 2007). Life

form (usually separating species into annual, biennial, perennial, shrubs, and trees) of a naturalized flora are the most frequently analyzed traits (Lloret et al. 2004). It is a general pattern that the life form spectrum of the naturalized taxa is characterized by a high proportion of herbaceous taxa (Pyšek et al. 2002; Lambdon et al. 2008; Weber et al. 2008). The naturalized flora of China is similarly characterized by a prevalence of annuals and perennial herbs among the naturalized plants. The high fraction of annuals (about 60%) in our list is likely driven by a high number of agricultural weeds. Elsewhere, annuals are often the least serious environmental weeds, suggesting that they are mainly weeds of disturbed grounds (Rejmánek and Richardson 1996; Weber 2003; Weber et al. 2008). Here, however, comparison of our data on naturalized plants to those compiled by other authors on invasive and “major” invasive plants reveals that proportions of perennial species are actually higher among invasives (Fig. 4). Our findings therefore provide new evidence that the role of life form in affecting the invasiveness of alien plants seems to be stage-specific: annuals are at an advantage during naturalization, while invasiveness seems to be associated with longer-lived life forms (Pyšek et al. 2003). The perennial life cycle, which often implies vegetative propagation and clonality, might play an important role in the invasion process and success for alien species (Liu et al. 2006; Hulme et al. 2008; Milbau and Stout 2008). A recent risk assessment concurs that the most notorious invasive plants in China are those with perennial life cycles, clonal growth ability, and origin in the American continent (Huang et al. 2009). The number of naturalized trees in China was relatively low (53, Appendix S1), compared with those in many other parts of the world (Weber 1997; Pyšek et al. 2002). There were two possible reasons for this; first because the introduction history of trees in China was relatively short (Zheng and Zhang 2006), and second because the time-lags of trees between introduction and naturalization were always much longer than those of grasses or herbs (Daehler 2009). However, it should be noted that in the last three decades, over 1,000 tree species (or cultivars) have been introduced to China as ornamental plants or forestry species (Zheng and Zhang 2006), and some of these newly-introduced trees (e.g., *Sonneratia apetala*) have spread rapidly and invaded many natural reserves. Therefore, much attention should be paid to the potential for naturalization and invasiveness of perennial aliens in China, especially the numerous newly-introduced woody species.

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