NeoBiota 15: 27–51 (2012)
doi: 10.3897/neobiota.15.3751
www.pensoft.net/journals/neobiota

REVIEW ARTICLE

A peer-reviewed open-access journal
NeoBiota
Advancing research on alien species and biological invasions

Plant invasions in China: an emerging hot topic in invasion science

Jian Liu[1,2], Hua Chen[2,3], Ingo Kowarik[1], Yiran Zhang[2,3], Renqing Wang[2,3]

1 *Department of Ecology, Technische Universität Berlin, Berlin, D 12165 Germany* **2** *Institute of Environmental Research, Shandong University, Jinan, 250100 P. R. China* **3** *Shandong Provincial Engineering and Technology Research Center for Vegetation Ecology, Shandong University, Jinan 250100, P. R. China*

Corresponding author: *Ingo Kowarik* (kowarik@tu-berlin.de)

Academic editor: *Ingolf Kühn* | Received 31 July 2012 | Accepted 30 November 2012 | Published 14 December 2012

Citation: Liu J, Chen H, Kowarik I, Zhang Y, Wang R (2012) Plant invasions in China: an emerging hot topic in invasion science. NeoBiota 15: 27–51. doi: 10.3897/neobiota.15.3751

Abstract

China has shown a rapid economic development in recent decades, and several drivers of this change are known to enhance biological invasions, a major cause of biodiversity loss. Here we review the current state of research on plant invasions in China by analyzing papers referenced in the ISI Web of Knowledge. Since 2001, the number of papers has increased exponentially, indicating that plant invasions in China are an emerging hot topic in invasion science. The analyzed papers cover a broad range of methodological approaches and research topics. While more that 250 invasive plant species with negative impacts have been reported from China, only a few species have been considered in more than a handful of papers (in order of decreasing number of references: *Spartina alterniflora, Ageratina adenophora, Mikania micrantha, Alternanthera philoxeroides, Solidago canadensis, Eichhornia crassipes*). Yet this selection might rather reflect the location of research teams than the most invasive plant species in China. Considering the previous achievements in China found in our analysis research in plant invasions could be expanded by (1) compiling comprehensive lists of non-native plant species at the provincial and national scales and to include species that are native to one part of China but non-native to others in these lists; (2) strengthening pathways studies (primary introduction to the country, secondary releases within the country) to enhance prevention and management; and (3) assessing impacts of invasive species at different spatial scales (habitats, regions) and in relation to conservation resources.

Keywords

Alien invasive species, biodiversity conservation, control, flora, ecological impact, management

Introduction

Biological invasions are a major driver of biodiversity loss worldwide (Mack et al. 2000, Millennium Ecosystem Assessment 2005, Gaertner et al. 2009, Pyšek and Richardson 2010, Vilà et al. 2011), and associated costs will continue to increase with the development of international trade and global change (Pimentel et al. 2005, Dehnen-Schmutz et al. 2007, Ding et al. 2008, Perrings et al. 2010). Concepts of modern invasion science took root in the 19th and early 20th centuries (Kowarik and Pyšek 2012), but the number of invasion studies has grown enormously since Elton (1958) published the classic book of *The Ecology of Invasions by Animals and Plants* (Richardson and Pyšek 2008, Kühn et al. 2011). Yet studies on plant invasions are still geographically biased, with an overrepresentation of studies in Western countries and a low presentation of developing countries in Africa or Asia (Pyšek et al. 2008, Nuñex and Pauchard 2010, Khuroo et al. 2011). This leads to an unbalanced understanding of biological invasions, which are often context specific (Richardson and Pyšek 2006). Studies in developing countries are now trying to fill the geographical gaps in invasion science research, which will be crucial to counteract negative impacts associated with plant invasions (Khuroo et al. 2011).

China is a vast country with rich biodiversity and a long history of species introductions (Xie et al. 2001, Ju et al. 2012). For example, in 126 B.C., Zhang Qian and his assistants introduced seeds of useful plants to China from central Asia, including alfalfa (*Medicago sativa* L.), pomegranate (*Punica granatum* L.), grape (*Vitis vinifera* L.), and safflower (*Carthamus tinctorius* L.) (Xie et al. 2001). Human disturbance and diverse introduction pathways, which usually increase in the wake of economic growth, are widely recognized as important drivers of biological invasions (Hierro et al. 2006, Meyerson and Mooney 2007, Hulme 2009, Essl et al. 2011a) and this holds particularly for China (Liu et al. 2005, Lin et al. 2007, Weber and Li 2008). While plant invasions in Europe have clearly increased since the 19th century (Lambdon et al. 2008) corresponding processes might have started later in China, likely due to the longer political and economic isolation of this country (Ding et al. 2008, Wang et al. 2011). However, with the rapid economic growth of recent decades, increasing numbers of plant introductions and linking of previously isolated regions through the establishment of new transport corridors have promoted plant invasions in China (Lin et al. 2007, Weber and Li 2008, Wang et al. 2011, Ju et al. 2012).

In the face of an accelerating pace of environmental change, the awareness of environmental problems associated with plant invasions has grown significantly in China during the last ten years (Li and Xie 2002, Xu et al. 2006). Xu et al. (2012) demonstrated that the number of invasive alien plant and animal species, i.e. species with negative impacts on biodiversity, economy or human health, increased exponentially since 1850. One of these invasive plant species is *Mikania micrantha* Kuhnt, known as “plant killer” in Chinese. This species covered nearly 40–60% of the woodlands of Neilingding Island at its peak and has been found to strongly impact local ecosystems (Zan et al. 2000, Feng et al. 2002, Wang et al. 2004).

The last decade yielded an increasing number of invasion studies in China. Xie et al. (2001) and Liu et al. (2001) have reviewed early papers on non-native plants in China which were published in Chinese (e.g., Hu and But 1994, Zhang and Han 1997, Ding and Wang 1998, Peng and Xiang 1999, Zan et al. 2000, Liu et al. 2001), and Ju et al. (2012) recently provided a review on different groups of plants and animals.

Here we review recent studies and research trends related to plant invasions in China, based on an analysis of papers referenced in the ISI Web of Knowledge. In particular, we were interested in the prevailing types of research (experiments, field investigations, modeling studies, reviews, or integrative analyses), the most studied species and the research topics covered by recent studies. For the latter, we screened for papers that addressed either biological features of introduced species, mechanisms, or impacts associated with plant invasions or control options. By analyzing the research trends and gaps, we also aimed to sketch future perspectives of studies on plant invasions in China.

Methods

Scope of papers

We screened the Web of Knowledge (ISI) for all papers published between 1945 and 2010 that are related to plant invasions in China. We used "all databases" including (1) Web of Science (1945–2010), (2) Current Contents Connect (1998–2010), (3) MEDLINE (1950–2010), and (4) Journal Citation Reports and analyzed all records published through the end of 2010. We found 643 papers when searching for the terms [plant* or weed*] and [invasion* or invasive* or introduced* or non-native* or neophyte*] and [China] in topic; 329 papers when searching for [invasive species] and [China]; and 143 papers when searching for [plant invasion in China]. Combining these approaches yielded matches of a total of 1,115 papers. By reading the abstracts of these papers, 187 papers were identified as addressing plant invasions in China. In the discussion of the results we also refer to some recently published papers. We are aware of some caveats in this approach since books on plant invasions are generally not recorded in ISI nor are some papers in non ISI-listed journals (e.g., Li and Xie 2002, Wang et al. 2004, Xu 2003, Xu and Ye 2003, Zheng and Ma 2010).

Paper analysis

We classified the obtained selection of 187 relevant papers according to the publication year, research type, research topic, and studied species. We differentiated the following research types: experimental studies, field investigations, modeling studies, reviews, and integrative analyses (Table 1). Experimental studies included papers based on experiments, usually done in lab or greenhouse, or manipulative field experiments. Field investigations included studies mainly based on analyses in the field, e.g. of distribution patterns of a single species or changes in community composition due to the naturalization of introduced species. We considered studies to be integrative analyses if they were based on databases of large numbers of species at the regional or national scales (> 300 km^2), usually aiming to reveal patterns in species traits or environmental factors related to plant invasions. In addition, we differentiated papers that provided reviews or used modeling approaches.

In a second step, we analyzed whether the papers addressed one or more of the following research topics: biological features of non-native plant species (e.g., morphological and physiological characters, clonal and propagation characteristics, genetic variation); mechanism of plant invasions (competition and other biotic interactions, human interference, enemy release, ecological, economic, or health impacts of plant invasions) and management approaches (mechanical, chemical, and biological methods). Some papers have been attributed to more than one category. For example, analyses of traits belong to the topic biological features, but when the paper demonstrated plant traits to facilitate invasions it had also been assigned to the research topic of mechanisms of invasions.

Results and discussion

Number of studies

The research in ISI revealed an increasing number of studies on plant invasions in China in the last decade, with an exponentially growing number of papers since 2005 (Figure 1). The review by Xie et al. (2001) on invasive species in China is the earliest paper referenced in ISI. No publications prior to 2001 were found in ISI, illustrating a rather short period of visibility of Chinese invasion studies to the international readership.

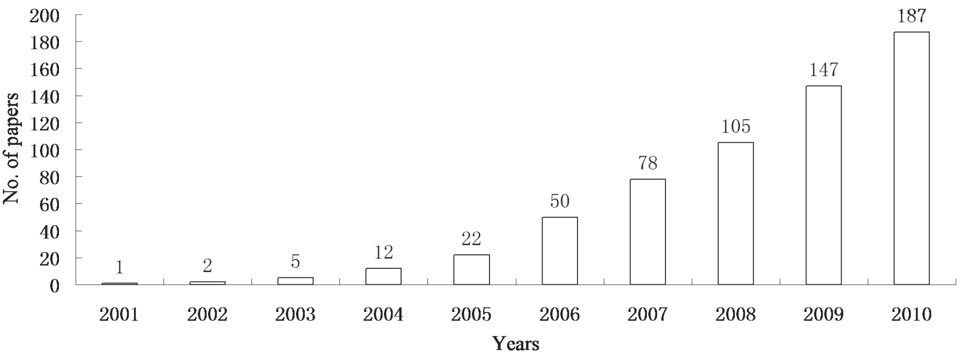

Figure 1. Cumulative numbers of papers on plant invasions in China based on a screening of the Web of Knowledge (1945–2010), see methods for details.

Main research types and topics

Most (89%) of the analyzed 187 papers addressed one or several non-native species studied by either field investigations (49%), experimental approaches (26%), modelling approaches (5%), or reviewed the existing knowledge on the species (10%; Table 1). Few papers (11%) offered integrative analyses some of which provided several lists of invasive plants in China at the national scale (Liu et al. 2005, Weber and Li 2008, Weber et al. 2008, Yang et al. 2010, He 2011). In addition, some recent papers listed naturalized plants (Wu et al. 2010, Jiang et al. 2011) and invasive plants (Liu et al. 2006, Weber and Li 2008, Huang et al. 2009, Xu et al. 2012). Yet, a comprehensive list of plant species non-native to China is missing thus far. In particular, casual non-native plant species are strongly underrepresented in existing lists. The most studied research topics (see below) included the characterization of biological features of introduced plant species and impacts associated with biological invasions, followed by studies on the control of invasive species. Compared to the latter issues, environmental factors related to plant invasions and other mechanisms that underlie plant invasions were studied to a lesser extent. Only a few papers (5%) modeled the distribution of non-native plant species in China (Table 1).

Most-studied species

The majority of the most-studied invasive plant species (Table 2) are herbaceous, and all are native to the Americas which generally comprise the most important donor regions for plants introduced to China (Feng et al. 2011, Huang et al. 2011). The perennial grass *Spartina alterniflora* Loisel. is clearly at the top of the list. An array of 47 papers cover all related research topics, with a clear focus on impacts that are complex and still in debate as reviewed by An et al. (2007) and Li et al. (2009). Consistently, most control studies

Table 1. Classifications of 187 papers on plant invasions in China, published in the period 2001–2010 and referenced in the ISI Web of Knowledge, according to research types and research topics: A – biological features of non-native plants; B – impacts of plant invasions; C – control approaches; D – invasibility or environmental factors related to plant invasions; E – mechanisms of plant invasions; F – predictions of the distribution of non-native plants. Some papers have been attributed to more than one category.

Research types	Research topics						
	All	A Traits	B Impacts	C Control	D Invasibility	E Mechanisms	F Predictions
Field investigations	91	35	33	14	8	6	1
Experimental studies	48	20	12	10	3	6	0
Integrative analyses	20	5	5	3	11	4	2
Reviews	19	11	6	9	1	1	1
Modeling studies	9	1	1	0	0	0	7
Total	187	72	57	36	23	17	11

addressed this species. The high numbers of studies on *S. alterniflora* might reflect the relevance of its impacts but might be also influenced by the fact that the invaded coastal ecosystems are easily accessible to researchers of many universities and national labs that are located in these areas. The second most studied species is *Ageratina adenophora* R.M.King & H.Rob. (=*Eupatorium adenophorum* Spreng.). *Mikania micrantha* Kuhnt, *Alternanthera philoxeroides* (Mart.) Griseb., and *Solidago canadensis* L. are the topics of between 10 and 20 papers each. Other species treated by only a few papers are *Ambrosia artemisiifolia* L., *A. trifida* L., *Chromolaena odorata* (L.) R.M.King & H.Rob., *Conyza sumatrensis* (Retz.) E.Walker, *Coreopsis grandiflora* Nutt. ex Chapm., *Flaveria bidentis* (L.) Kuntze, *Galinsoga parviflora* Cav., *Lantana camara* L., *Ipomoea cairica* (L.) Sweet, *Parthenium hysterophorus* L., *Rhus typhina* L., *Robinia pseudoacacia* L., *Solanum rostratum* Dunal, *Spartina anglica* C.E.Hubb. and *Wedelia trilobata* (L.) Hitchc.

The current focus on a rather small group of invasive plant species must not necessarily reflect the importance of a given non-native species in terms of ecological or economic impacts but might be considerably affected by the location and scientific background of research teams. Yet the much higher number of 265 invasive plant species (Xu et al. 2012) clearly indicates strong research needs to study a broader range of invasive species in China.

Usually, papers on invasive plant species address species that are non-native to the total area of China. Species that are native to a region in China but non-native to one or more others are rarely studied. One example is *Syzygium jambos* (L.) Alston, which is native to some provinces of China but has been reported as an invasive plant species in Hong Kong (Leung et al. 2009). Another example is the tree *Ailanthus altissima* (Mill.) Swingle which had been cultivated for a long time beyond its native range in China (Hu 1979). Today, it is not only invasive in many parts of the world (Kowarik and Säumel 2007) but also started to invade areas in China beyond its native range, e.g., in the Xinjiang province since the 1990s (Huang 1997, Säumel, personal communication). Analyzing the spread and impacts of species beyond their native ranges in China thus remains a challenge for future research.

Biological features

In 72 papers, the biological features of plant species non-native to China were analyzed, mostly by field studies and experimental approaches (Table 1). More than 20 papers addressed physiology, genetics, or regeneration patterns of introduced species. Fewer papers are related to morphological features and seed ecology.

Some studies illustrated physiological characters of introduced species that contribute to their invasion success. For example, Song et al. (2009) found that the increase in photosynthetic rate due to elevated CO_2 concentrations was significantly higher in non-native than in native species. In a study on the Yangtze River system, Jiang et al. (2009) revealed a competitive advantage of *Spartina alterniflora* over native species (*Phragmites australis* (Cav.) Steud. and *Scirpus mariqueter* Tang & F.T.Wang) through higher maximal net photosynthetic rate and a longer growing season.

Table 2. Most-studied alien plant species in China and related research topics (number of studies referenced in the ISI Web of Knowledge, 2001–2010). The native range and life form of the species are also shown. PG – perennial grass; BS – broadleaf shrub; PV – perennial vine; H – perennial herb; APH – aquatic perennial herb. The codes for the research topics A–F are the same as in Table 1.

Species	Life. Form	Native range	All	A Traits	B Impacts	C Control	D Mechanisms	E Invasibility	F Predictions
Spartina alterniflora	PG	America	47	9	30	8	3	3	1
Ageratina adenophora	BS	North America	27	12	5	4	3	5	1
Mikania micrantha	PV	America	19	8	4	7	1	0	0
Alternanthera philoxeroides	PH	South America	12	9	0	4	4	1	0
Solidago canadensis	PH	North America	10	4	2	1	2	1	2
Eichhornia crassipes	APH	South America	7	3	0	4	0	0	0
Total	-	-	122	45	41	28	13	10	4

Studies on the genetic variation or diversity of non-native plants revealed a very low genetic diversity in most clonal invasive plants such as *Alternanthera philoxeroides* and *Eichhornia crassipes* (Mart.) Solms (e.g., Ye et al. 2003, Ren et al. 2005, Wang et al. 2005, Li et al. 2006), while a relatively high genetic diversity has been found for a few species, such as *Coreopsis grandiflora* (Liang et al. 2008) and *Conyza sumatrensis* (Ren et al. 2010). Hao et al. (2011) illustrated a higher probability of spreading and covering a broad range in self-compatible than in self-incompatible species of Asteraceae in China.

The exploration of larger databases revealed that nearly half of 126 invasive species are clonals, and these are more frequent than other non-native plant species (Liu et al. 2006, Huang et al. 2009). Correspondingly, the top 13 plant invaders in China (based on the number of published papers) are clonally growing perennials (Huang et al. 2009). Greenhouse experiments in *Alternanthera philoxeroides* and *Spartina alterniflora* supported the idea that clonal integration and phenotypic plasticity of clonal plants have enhanced their invasion success (e.g., Geng et al. 2006, Liu et al. 2008, Yu et al. 2009, Zhao et al. 2010). By using genetic techniques, Dong et al. (2006) found that sexual reproduction facilitated the initial establishment of *Solidago canadensis* populations, while clonal growth led to a subsequent expansion of established populations.

Several studies analyzed the germination and seed banking of invasive species. Seed bank studies illustrated the role of sexual regeneration in the range expansion of clonal plants such as the highly invasive *Ageratina adenophora* and *Spartina alterniflora* (Shen et al. 2006, Xiao et al. 2009). Plasticity in seed germination and seed size was considered to be a trait that allowed for acclimation to different environmental conditions and facilitated invasions by *M. micrantha* and *Ageratina adenophora* (Yang et al. 2005, Li and Feng 2009).

Invasion impacts

There were 57 papers related to impacts of plant invasions in China (Table 1), affecting native plants, birds and other animals, soil biota, climate and economy. Several papers revealed negative effects of *Spartina alterniflora* on native plants, birds, and macrobenthic invertebrate communities (reviews by An et al. 2007, Li et al. 2009, Gan et al. 2009, Xie and Gao 2009). Yet, impacts due to *Spartina* invasions are still controversially discussed. Field research suggested a significant decrease in the abundance of native species and coverage of resident vegetation as well as negative impacts on birds feeding on native plants (Chen et al. 2004). Other studies, however, identified positive impacts of *S. alterniflora*, such as an enhanced storage of carbon dioxide (Liao et al. 2007), an increased inorganic nitrogen pool in the soil (Peng et al. 2010) and better shelter and food sources for a native crab species (Wang et al. 2008).

Ageratina adenophora was found to inhibit native species by altering soil microbial communities (Niu et al. 2007), while *Solidago canadensis* and *M. micrantha* can reduce the seed germination of native plants by allelopathic effects (Yang et al. 2007, Wu et al. 2008). A couple of papers described changes in soil conditions and soil biota due to invasions by, e.g., *M. micrantha* (Chen et al. 2009) and *A. adenophora* (Niu et al. 2007). A recent study illustrated, that allelopathic effects of the latter species can be reduced by native soil biota (Zhu et al. 2011). Chen et al. (2011) surprisingly found that *Coreopsis grandiflora* enhanced the functional diversity of soil microbial communities of invaded habitats.

Rather few papers addressed economically relevant invasion impacts. The review by Xie et al. (2001) as well as the integrative study by Xu et al. (2006) highlighted the relevance of economic impacts due to biological invasions for several sectors such as agriculture, forestry, water transportation, and human health. The authors estimated a total of USD14.45 billion in losses caused by all groups of invasive species to China in the year of 2000 but did not differentiate the contribution of plants and other organism groups to these losses. Xu et al. (2006) also stated that sound and strict case studies are lacking – and this still holds today.

To our surprise no paper particularly addressed human health, although some books recorded the harmful impacts of invasive plants on human health, in particular of allergenic plants (*Ageratina adenophora, Ambrosia* species, Li and Xie 2002, Xu 2003, Xu and Ye 2003).

Control and management

Most papers on control or management of plant invasions addressed biological control (Table 1). Several papers explored approaches of using the native parasite *Cuscuta campestris* Yunck. to restrain the non-native *M. micrantha* (e.g., Shen et al. 2005, Lian et al. 2006b, Zhao et al. 2008, Yu et al. 2008, Yu et al. 2009). The beetle *Agasicles hygrophila* Selman & Vogt was revealed to be a useful and safe biocontrol agent of *Alternanthera* *philoxeroides* as it had only limited effects on the non-target species *Alternanthera sessilis* (L.) R.Br. ex DC. (Li and Ye 2006, Lu et al. 2010a). The ant *Dorylus orientalis* Westwood was found to be a potential control agent of *Ageratina adenophora* (Niu et al. 2010).

While most studies on biological control focus on invasive plants as target species, some ecologists have begun to study the restoration of native plant communities after performing control. For example, field studies found that native *Cuscuta campestris* could not only restrain the non-native *M. micrantha* but might also contribute to the recovery of native communities by enhancing the availability of soil resources for native species (Yu et al. 2008, Yu et al. 2009).

Mechanical control approaches were studied in a few papers. The main target species were *Spartina alterniflora* (Li and Zhang 2008, Gao et al. 2009, Tang et al. 2009a) and *M. micrantha* (Lian et al. 2006a). Mostly, methods of mechanical control were tested. For example, Lian et al. (2006a) found that periodic cutting reduced the competitiveness of *M. micrantha* and fostered the growth of native species. The authors consider this approach an effective and easy method to reduce the dominance of *M. micrantha* although control of the invader was not perfect. Moreover, it also enhanced the growth of some other non-native species. Other papers covered chemical control approaches but most of them were reviews (e.g., An et al. 2007, Pan et al. 2007). The functioning of different or combined control approaches has been rarely studied thus far. As an exception, Guo et al. (2009) analyzed the effects of herbicides, uprooting, and cutting in the flowering stage on the sexual regeneration of *Solidago canadensis*. To reduce seed production the authors recommend herbicide application at the flower bud stage or uprooting at the flowering stage. Cutting flowering branches for ornamental purposes should be avoided

Policies related to the management of invasive plants were covered by a small selection of papers, and most of them were reviews. As control approaches are usually costly, an economically beneficial use of the harvested biomass could increase the efficiency and sustainability of control measures. Lu et al. (2010b) suggested an innovative approach in the field of bio-resource engineering. Their experiments showed that mixing biomass of the invasive water hyacinth (*Eichhornia crassipes*) with pig manure leads to a much higher biogas production than by using pig manure alone.

Underlying mechanisms

A couple of papers considered mechanisms underlying plant invasions in China (Table 1). Many of these were studies addressing the competition between introduced and native plant species. For example, *Spartina alterniflora* was found to have a competitive advantage over native plant species (Chen et al. 2004). Other studies illustrated significant differences in the response of native and invasive plants (*Mikania micrantha*, *Wedelia trilobata*, *Ipomoea cairica*) to elevated concentrations of CO_2 and discussed these results in terms of a future success of invasive species in the face of ongoing increases in atmospheric CO_2 concentrations (Song et al. 2009, Song et al. 2010). Wang et al. (2011)

found that increased temperatures enhance the aboveground biomass in *Ipomoea cairica* as well as the phytotoxicity of aqueous leachates from fresh leaves of this introduced liana. They concluded that global warming will foster invasions by this species.

Some studies tested the EICA hypothesis. For example, Feng et al. (2009, 2011) found that the invasive *Ageratina adenophora* have evolved an increased N allocation to growth and a reduced N allocation to defenses. Gao et al. (2011) provide evidence of the correlation between epigenetic reprogramming and the reversible phenotypic response of *Alternanthera philoxeroides* to particular environment in China. Pan et al. (2012) studied five populations of this invasive species and found that slow-growing genotypes experienced a stronger enemy release than fast-growing genotypes.

Biotic interactions other than competition have been studied to a lesser extent in China. Some papers studied the role of soil biota (e.g., Chen et al. 2011, Zhu et al. 2011). Based on studies of *Ageratina adenophora*, for example, Yu et al. (2005) suggested that non-native plants might inhibit native plants by changing soil microbe communities.

A few papers, mostly integrative data analyses, addressed ways of human interference to invasion processes. The fast growing economy of China has been often suggested to accelerate plant invasions through an enhanced international trade and associated species introductions (Lin et al. 2007, Ding et al. 2008, Wu et al. 2010), but studies on the relevance of different pathways are scarce (but see Xu et al. 2012 on the introduction pathways of invasive plant species). Data on the introduction history of non-native plants are limited, but analyzing the history of 123 plant species showed a continuous influx of non-native species to China after 1800 (Huang et al. 2011). However, much more species are known as naturalized in China (861 species according to Jiang et al. 2011), and casuals are usually underrepresented in species lists. It remains thus an open question whether the influx of non-native species since 1800 took place linearly or rather exponentially as indicated by the exponential growth of the number of invasive alien species of plants and animals since 1850 (Xu et al. 2012). Deeper insights into the history of plant invasions are an intriguing area of future research.

The example of *Parthenium hysterophorus* illustrates with evidence from nuclear and chloroplast DNA that multiple introductions were responsible for subsequent invasions in China (Tang et al. 2009b). As in other parts of the world, annuals were mostly introduced accidentally while perennials were mainly introduced intentionally (Xu et al., 2004).

Environmental factors related to invasions

Some studies related environmental factors to plant invasions. The decreasing number of invasive plant species from the south to the north of China could be related to climatic factors (Wu et al. 2006). Recent studies illustrated the relative predictive power of biogeographic and socio-economic factors in explaining current distribution patterns (Feng et al. 2011, Huang et al. 2011). Biogeographic factors mainly explained the distribution of species introduced from Central and South America, while socio-economic factors were more important for species introduced from Eurasia or North America (Huang et al. 2011). Other studies illustrated the significance of environmental factors at the habitat scale. Lu and Ma (2006) and Dong et al. (2008), for example, found that roadside habitats favor invasions by *Ageratina adenophora* and revealed a decreasing abundance of this species with increasing distance from the road. A field survey in southeast China found that *Alternanthera philoxeroides* dominates in microhabitats with high soil nutrients and water availability, whereas the cover of its native congener *A. sessilis* was relatively high in habitats with low soil nutrients and low water availability. High resource availability therefore appears to facilitate invasions by *A. philoxeroides* (Pan et al. 2006). A study on tropical East Asian islands (some belonging to China) found that closed-canopy forests appear to resist plant invasions (Corlett 2010).

Modelling the distribution of non-native plants

Only a few papers modelled the potential distribution of non-native species (Table 1), based on current environmental factors and biological features of the species, while no paper addresses the potential abundance of non-native plants in China. For example, ecological niche modelling was used to predict the invasion potential of *Ageratina adenophora* on the basis of occurrence points within colonized areas (Wang and Wang 2006). Using datasets on known localities invaded by *A. adenophora* and the environmental variables generated by the genetic algorithm for rule-set production (GARP) model, the potential future distribution of this invasive plant was modeled (Zhu et al. 2007). Using the homoclime approach, Lu et al. (2007) found that the potential range of *Solidago canadensis* in China is remarkably larger than the current range. A cellular automata model in conjunction with remote sensing and a geographical information system (GIS) was used to simulate the expansion process of *Spartina alterniflora* and support the hypothesis of space pre-emption as well as subsequent range expansion (Huang et al. 2008).

Conclusions

The exponentially increasing number of papers on plant invasions in China in the last decade (Figure 1) suggests plant invasions in China to be an emerging hot topic in invasion science. The analyzed papers cover a broad range of methodological approaches and research topics and clearly enhanced the understanding of plant invasions in China, in particular by compiling species lists, analyzing taxonomic and geographical patterns, and studying species- and environment-related mechanisms that might shape plant invasions and their associated impacts. Although plant invasions have been acknowledged as an important environmental risk to China, only six invasive species have been studied in detail thus far (Table 2). This sharply contrasts to a much higher number of invasive species (Xu et al. 2012). Further invasion research in China is thus strongly needed and would also help counteracting the continuing global imbalance in the understanding of invasion patterns (Richardson and Pyšek 2006).

We argue for an additional reason for encouraging further studies on plant invasions in China. This country has undergone far-reaching socio-economic changes in a relatively short period of about 30 years, and several drivers of this change are well known to enhance biological invasions (Lin et al. 2007, Ding et al. 2008, Weber and Li 2008, Huang et al. 2010). Experience from other regions indicates that a significant part of the "invasion echo" following economic changes might come decades or even centuries later. In different countries, recent invasion patterns could be better explained by economic parameters from the past (Sullivan et al. 2004, Essl et al. 2011a), and decades to centuries can elapse between the first introduction of a species to a region and subsequent invasions (Kowarik 1995, Aikio et al. 2010). Thus, the enormous recent increase in urbanization, transport corridors, and use of introduced plants in horticulture, landscaping, and forestry will certainly evoke a wave of future plant invasions in China (Ding et al. 2008, Ju et al. 2012). Strengthening invasion research in China, with special emphasis on the points described below, could help to mitigate foreseeable economic damage and negative impacts on the high biological diversity of this country. Some of the following points are generally relevant, others are more specific for China due to the special history of this country.

Lists of non-native species at regional and national scales

Although some lists of naturalized plants in China have recently been compiled (Wu et al. 2010, Jiang et al. 2011) and some on invasive species already exist (Liu et al. 2005, Weber and Li 2008, Weber et al. 2008, Huang et al. 2009, Xu et al. 2012), a comprehensive list of all non-native plants in China is still lacking. China is a large country in area with starkly varying environmental conditions. Thus, complete lists of non-native species compiled at the regional scale (e.g., provinces or metropolitan areas, Wang et al. 2011) and then aggregated at the national scale might be useful. As in other regions (Lambdon et al. 2008), two categories of non-native species can then be differentiated: species non-native to China and species native to one part of China but non-native to others. This differentiation is promising as species from both categories can induce severe invasion impacts. At the province scale, the number of non-native species can be underestimated if only species non-native to a larger unit, the whole country, are considered non-native (see Guo 2011, Pyšek 2011). Additional information on the taxonomy, native range, residence time, biological characters, and propagule pressure of non-native plants as well as on invaded habitats would help to reveal traits related to invasiveness and habitat invasibility and might strengthen the use of such lists in early warning approaches (Pyšek et al. 2004, Lambdon et al. 2008).

There is growing evidence that the time since the first introduction of a species to new range matters in terms of habitat occupation, impacts and response to climate (Pyšek et al. 2005, Jarošik et al. 2011). Hence, classifying non-native plants based on different lengths of their invasion history in China could help to better understand invasion processes and associated impacts in the long run. Many early introductions that have experienced a long-term selection and adaptation to their new range are known for China (Xie et al. 2001), and considering the performance of non-native species with a long invasion history might help to predict the future performance of species with a much shorter introduction history (La Sorte and Pyšek 2009). While a temporal differentiation of archaeophytes and neophytes (pre-Columbian and post-Columbian introductions, respectively) is useful for European or American studies (Pyšek et al. 2005) another definition of "early" and "late" introductions might be appropriate for China because of the different history of this country.

Invasion pathways

Human-mediated dispersal is a key process in plant invasions, and identifying and assessing the strength of dispersal vectors helps to set priorities in prevention and management (Carlton and Ruiz 2005, Kowarik and von der Lippe 2007, Hulme et al. 2008). Thus far, a few papers have studied the role of human interference on plant invasions in China. Xu et al. (2012), for example, found that about two thirds of 265 invasive plant species in China were intentionally introduced. As in other regions (Křivánek et al. 2006, Dehnen-Schmutz et al. 2007, Essl et al. 2010) horticulture and forestry are important introduction pathways. Yet as most plants are dispersal-limited even after an initial introduction to a country, subsequent secondary releases within a region often function as an important driver of plant invasions for a long period of time after the initial introduction to a country (Kowarik 2003). The case of *Spartina alterniflora* shows that repeated plantings can have highly relevant ecological consequences (An et al. 2007, Li et al. 2009). Information on negative invasion impacts of a given species can be used for regulating the relevant invasion pathways. One example is the recommendation to abandon the previously common practice of planting the North American tree *Rhus typhina* in Beijing (Wang et al. 2008).

The recent economic growth of China is associated with an increasing development of road systems, the linking of watersheds by canals, and a powerful growth of cities. The huge project of water transfer from the southern part of China to the northern part (namely the South-to-North Water Transfer Project of China), which will deliver about 45 billion m^3 of water annually from the Yangtze River to the north of China (Yang and Zehnder 2005, He et al. 2010), will also provide a new pathway for the dispersal of aquatic plants. In consequence, future invasion risks will result from interactions between the increased propagule pressure of non-native plants due to greenings of the built infrastructure and new or more effective dispersal pathways, provided either by roads (Pauchard and Alaback 2004, von der Lippe and Kowarik 2012) or waterways (Thomas et al. 2006, Säumel and Kowarik 2010, Jacquemyn et al. 2010). Consistently, road habitats appear to enhance invasions by *Ageratina adenophora* in China (Lu and Ma 2006, Dong et al. 2008). A better understanding of habitat- or dispersal-related mechanisms would help to counteract such invasions by optimizing either prevention or management efforts. As the role of socio-economic factors in driving plant invasions is often underestimated, both human-mediated and natural factors should be considered in analyzing patterns of plant invasions (Liu et al. 2005, Meyerson and Mooney 2007).

Impacts and management

Risk assessment and management of invasive plants are essential approaches to prevent potentially harmful new introductions or mitigate negative impacts of already introduced species. While classifications of species as "invasive," i.e., problematic, in other regions might be helpful in early warning systems ("invades elsewhere" criterion; Williamson 1999), setting priorities in management would certainly profit from regionally based impact assessments (Essl et al. 2011b). As the performance of non-native plant species depends on regional and local environmental conditions, impacts might differ significantly (Thiele et al. 2011, Vilà et al. 2011). The same species can affect biodiversity negatively or positively in different regions (e.g., Jäger et al. 2009, Fischer et al. 2009). As a consequence, existing (regional) lists of invasive species in China could be expanded by adding information on conservation resources that are (or might be) affected by an invasive species and on the conservation value of these resources (Bartz et al. 2010). As control actions often fail, monitoring the desired decline of non-native target species as well as effects on other species (e.g. Yu et al. 2008, 2009) would help to optimize control. Moreover, management actions can be combined with approaches of ecological restoration (Gaertner et al. 2012).

Acknowledgements

We thank Professor Shili Miao, Ingolf Kühn and two anonymous reviewers for comments on earlier versions of the paper and Kelaine Vargas for improving our English. Jian Liu was financially supported by the Key Science and Technology Project of Shandong Province (No. 2011GGH21605) and the China Scholarship Council for a research stay at Technische Universität Berlin.

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