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Authors: Ding, Jianqing, Mack, Richard N., Lu, Ping, Ren, Mingxun, and Huang, Hongwen

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China's Booming Economy Is Sparking and Accelerating Biological Invasions

JIANQING DING, RICHARD N. MACK, PING LU, MINGXUN REN, AND HONGWEN HUANG

China has undergone enormous economic growth in the last 25 years, largely as a result of greatly increased international trade. This burgeoning trade has triggered environmental threats from an expanding list of biological invaders: nonnative species previously unknown in China (e.g., the American vegetable leaf miner, the fall webworm) have arrived and are already causing damage to China's environment and economy. Huge construction projects, such as the Three Gorges Dam and the recently completed rail link to Tibet, could further spread invasive species to once-isolated portions of the country. The environmental risks from this onslaught are immense: China is one of the world's hotspots of biodiversity with about 30,000 native species of vascular plants and at least 2340 species of native terrestrial vertebrates. Fostering governmental and public awareness in China of the costs of invasive species and the multiple benefits of their prevention and control will be key to countering this menace.

Keywords: Ageratina adenophora, Eichhornia crassipes, *emerald ash borer, international trade, Three Gorges Dam*

Each nation receives and contributes to the world-wide pool of immigrant species through its international trade (Ruiz and Carlton 2003); some of these immigrants become invasive and wreak enormous damage in their new ranges (Mack et al. 2000). The list of species native to China that are now invasive elsewhere includes such well-known pests as the Asian long-horn beetle (*Anoplophora glabripennis* [Motschulsky]), the emerald ash borer (*Agrilus planipennis* [Fairmaire]), the multiflora rose (*Rosa multiflora* [Thunb.]) and white pine blister rust (*Cronartium ribicola* [J. C. Fisch.]). In turn, China has received alien species that have become naturalized and even invasive (tables 1, 2).

These invaders could be merely the forerunners of an onslaught into China. The rate at which introduced species arrive, including those that become invasive, is accelerating in step with China's surging economic growth since implementation of its landmark "Reform and Opening" policy in 1978. In the last 10 years, China has had the world's highest growth rate in gross domestic product (GDP), such that the total value of its imports and exports grew from US$20.6 billion in 1978 to a staggering US$1422.1 billion in 2005 (NBSC 2006). Such phenomenal growth in international trade portends environmental damage on a potentially huge scale, because the volume of a nation's international trade and the numbers of recently arriving invasive species form a strongly positive correlation (Levine and D'Antonio 2003).

The effects of an invasive species can be immediate, conspicuous, and profound. For example, Beijing, the host for the 2008 Summer Olympic Games, launched a concerted campaign in 2006 against the introduced fall webworm (*Hyphantria cunea* [Drury]), a recent invader from North America that has swiftly devastated Beijing's urban landscape by defoliating more than 200 plant species, including valued ornamental trees (Jia 2006). This introduced insect is however only one of more than 400 alien species now considered invasive in China (Xie et al. 2001).

Although all nations face a growing threat from biological invasions (di Castri 1989), the challenge for China in blocking these invaders' advance may be especially formidable. The growth of China's industrial and transportation infrastructures, including many mammoth construction projects, are facilitating introduced species' dispersal and establishment throughout the country, thereby setting the stage for potentially rampant environmental damage. For China, as well as for any other nation, both the causes and potential solutions of these pending environmental crises deserve enhanced research, public education, and governmental attention (Lodge et al. 2006).

Jianqing Ding and Mingxun Ren are with the Wuhan Botanical Garden and the Wuhan Institute of Botany, Chinese Academy of Sciences, Wuhan, China. Richard N. Mack is with the School of Biological Sciences at Washington State University in Pullman. Ping Lu was with the Wuhan Botanical Garden and the Wuhan Institute of Botany when this article was prepared, and is now with the Resources and Environmental Sciences College at the Northeast Agricultural University in Harbin, China. Hongwen Huang (e-mail: huanghw@mail.scbg.ac.cn) is with the South China Botanical Garden and the South China Institute of Botany at the Chinese Academy of Sciences in Guangzhou, China.

Table 1. Dates of introduction and outbreak for 17 invasive plant species in China.

Scientific name	Common name	Introduction (first detection)	Outbreak
Ageratina adenophora (Spreng.) R. M. King et H. Rob.	Crofton weed	1935	1960s
Alternanthera philoxeroides (Mart.) Griseb.	Alligator weed	1935	1980s
Ambrosia artemisiifolia L.	Giant ragweed	1930s	1980s
Ambrosia trifida L.	Common ragweed	1960s	1980s
Azolla filiculoides Lam.	Azolla	1977	Post-2000
Chromolaena odorata (L.) R. M. King et H. Rob.	Siam weed	1934	1980s
Conyza sumatrensis (Retz.) E. Walker	Broadleaf fleabane	1850	Post-2000
Eichhornia crassipes (Mart.) Solms	Water hyacinth	ca. 1930	1980s
Eupatorium catarium Veldkamp		1990	Post-2000
Flaveria bidentis (L.) Kuntze, R. M. King et H. Rob.	Smelter's bush	2001	2005
Mikania micrantha H. B. et K.	Mile-a-minute weed	1984	1990s
Parthenium hysterophorus L.	Parthenium weed	1926	1980s
Pistia stratiotes L.	Water lettuce	Pre-1700	Post-2000
Plantago virginica L.	Virginia plantain	1951	1990s
Solidago canadensis L.	Canada goldenrod	1935	1980s
Spartina alterniflora Loisel.	Smooth cordgrass	1979	1990s
Spartina anglica C. E. Hubb.	Common cordgrass	1963	1980s

Note: References for this table are available online at *www.bioinvasion.net/PDF/supplementary%20tables.pdf.*

Table 2. Dates of introduction and outbreak for 22 invasive animal species in China.

Scientific name	Common name	Introduction (first detection)	Outbreak
Achatina fulica Ferussac	Giant African land snail	1930	1979
Ampullaria gigas Spix	Amazonian snail	1981	1988
Blattella germanica (Linnaeus)	German cockroach	1935	1960
Brontispa longissima	Coconut leaf beetle	2002	2002
Bruchus rufimanus (Gestro)	Broad bean seed beetle	1940	1960
Bursaphelenchus xylophilus (Steiner et Buhrer) Nickle	Pine wilt nematode	1982	1982
Callosobruchus maculatus (Fabricius)	Cowpea weevil	1960	1960
Dendroctonus valens LeConte	Red turpentine beetle	1998	1999
Eriosoma lanigerum (Hausmann)	Woolly apple aphid	1914	1950s
Hemiberlesia pitysophila Takagi	Pine needle hemiberlesian scale	Late 1970s	1982
Hyphantria cunea (Drury)	Fall webworm	1979	1980
Laspeyresi pomonella L.	Codling moth	1957	Early 1980s
Liriomyza sativae Blanchard	Vegetable leafminer	1993	1995
Lissorhoptrus oryzophilus Kuschel	Rice water weevil	1988	1988
Myocastor coypus (Kerr)	Coypu	1953	1990
Mytilopsis sallei (Recluz)	Black-striped mussel	1977	1982
Opogona sacchari (Bojer)	Banana moth	Late 1980s	1995
Oracella acuta (Lobdell)	Loblolly pine scale	1988	1993
Oreochromis spp.	Tilapia	1957	1980
Procambius clarkii Girard	Crayfish	1930	1980
Solenopsis invicta Buren	Red imported fire ant	2004	2005
Viteus vitifoliae (Fitch)	Grape phylloxera	1895	1935

Note: References for this table are available online at *www.bioinvasion.net/PDF/supplementary%20tables.pdf.*

Growth of transportation networks: Increasing pathways for invaders

As any nation opens its borders more to commerce, it automatically increases the opportunities for the entry of invasive species. A total of 253 airports, seaports, and railway and motorway stations in China—double the number in 1987 (CC 2007)—are now international ports of entry. China's exports and imports by seaports have risen from 311.5 million metric tons in 1985 to 2538 million metric tons in 2004 (Cui 2005), and potentially invasive species can be accidentally transported as hitchhikers in or on cargo containers, as well as deliberately transported (primarily plants and vertebrates). International travelers can also deliberately or accidentally introduce species that later prove to be invasive (Ruiz and Carlton 2003). Here again, the magnitude of this travel in China has increased enormously, to 16.93 million passengers in 2004 (NBSC 2006), almost triple the number in 1995. China's expanding domestic transportation networks almost certainly facilitate the spread of potentially invasive species across the country through myriad deliberate and accidental modes of transport (Ruiz and Carlton 2003). For example, the total length of express highways in China has grown from 1000 kilometers (km) in 1988 to 40,700 km in 2005 (NBSC 2006). These improved roadways serve an escalating number of the nation's civilian vehicles, which have increased to 26.93 million—a 20-fold increase since 1978. Simultaneously, the number of passengers on domestic flights was 138.27 million in 2005, compared with just 2.31 million in 1978 (NBSC

2006) (for other transportation changes, see figure 1). The transportation record in the last 25 to 30 years for Shanghai, China's largest commercial port, is emblematic of the greater facility with which nonnative species can move inland. The volume of domestic-bound freight transported from Shanghai via roads increased to 326.84 million tons in 2005 from 72.84 million tons in 1980 (SSB 2006); similar increases have occurred for freight carried by other modes of transportation (figure 2). Among such rapidly expanding systems of distribution, the opportunity for the accidental domestic transport of nonnative species is substantial because the system of cross-provincial plant and animal quarantine and inspection is inadequate (Wang 2001).

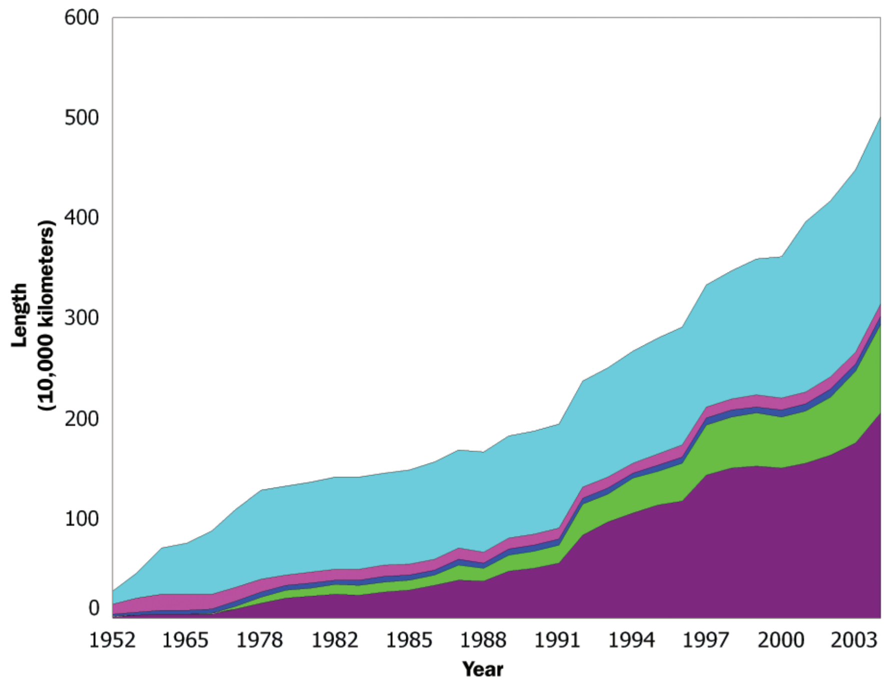

Figure 1. Growth of transport in China, 1952–2005. Shown is the total length of all trips taken by highways (light blue), waterways (pink), railways (dark blue), international airlines (green), and domestic airlines (purple). Data are from the China Statistical Yearbook *for 2005 (NBSC 2006).*

Newly arrived invasive species: A heavy price for rapid economic growth

China's enormous economic growth has come with a high environmental cost in air and water pollution, forest fragmentation, and a looming loss of biodiversity (Liu and Diamond 2005, Beardsley 2007, Grumbine 2007). Biological invaders are both beneficiaries of and contributors to this damage. The total numbers of harmful alien animals, plants, and other pest organisms intercepted at Chinese borders grew at least 10-fold from 1990 to 2005 (figure 3; Xia 2004, Chen et al. 2005). Invasive animal species, mainly insects, have also increased more than 30% to 76 species from 1990 to 2003 (Xu et al. 2004). For invasive plant species, the first literature-based survey in 1995 listed 58 species (Ding and Wang 1998), but a national survey from 2001 to 2003 discovered 188 species, half of which had been intentionally introduced (Xu et al. 2004).

We have assembled records for first detection and "pest outbreak" (i.e., when the species was first considered invasive) for the 17 invasive plant species, and 22 animal species, in China for which data are available. Of 17 invasive plant species (introduced mostly after 1930), 16 species' outbreaks have occurred since 1980, causing much damage to the economy and the environment (table 1). For

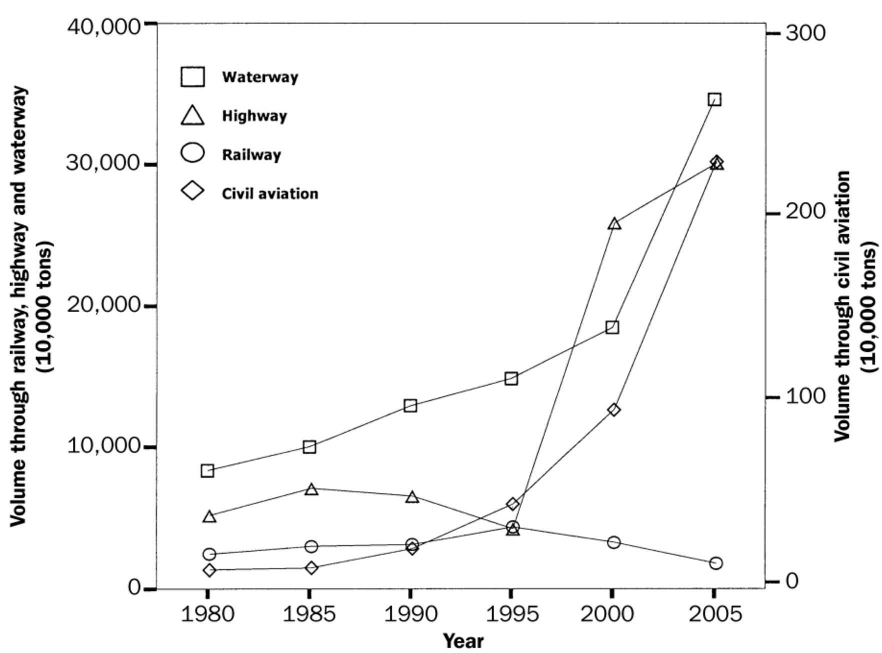

Figure 2. Volume of imports (metric tons) transported through the port of Shanghai by railways, highways, waterways, and civil aviation for the period 1980–2005. Data are from the Shanghai Statistical Yearbook *(SSB 2006).*

example, Canada goldenrod, *Solidago canadensis* L., which was introduced into China from North America as an ornamental plant in the 1930s, has escaped and swiftly invaded more than 20 provinces in the last 10 years through its wide dispersal by the domestic nursery and garden industries (Dong et al. 2006).

Invasive insects have spread more rapidly than plants. Eleven of 22 alien animal species, mainly insects, including all the most damaging invasive agricultural and forest pests in China (Li and Xie 2002), were introduced in the last 20 to 30 years (table 2). Their spread has often been conspicuous soon after their arrival; for example, the American vegetable leaf miner, *Liriomyza sativae* (Blanchard), was listed as a domestic quarantine insect soon after it was first detected in Sanya, Hainan Province, in December 1993. This leaf miner reached invasive proportions in 21 provinces by 1995, just one year after its entry into China—an exceptionally fast-moving invasion facilitated in large measure by the domestic transport of leaf miner–infested crops, such as vegetables (Wang 1997). It now occurs throughout China, except in Tibet (Xizang), and causes annual economic losses amounting to about US$80 million (Li and Xie 2002). Intriguingly, most of these plant and animal invasions—even for species in China long before 1980—have become invasive only in the last 25 to 30 years (tables 1, 2), coincident with the proliferation of domestic transportation networks radiating from ports such as Shanghai.

Benefits from industrial development projects versus disturbance and invasion

Disturbance often provides the opportunity for the establishment and proliferation of invasive species (Mack 1989, Hobbs and Huenneke 1992). Coincident with its high GDP, China may also rank first among nations in its wholesale ecosystem disturbance caused by massive construction of dams, canals, highway and railway networks, bridges, public and private buildings, and mines. China's investment in capital construction has risen sharply since the 1990s (figure 4). The area occupied by newly constructed public and private buildings in 2004 was 2919 million square meters (an annual measure of construction), an eightfold increase since 1985. The much-heralded Three Gorges Dam (TGD), the South-to-North Water Diversion Project, and the West-East Gas Pipeline Project are the world's three biggest construction projects (Liu and Diamond 2005), and might also rank as the three largest ecosystem disturbances on the globe; each provides extensive opportunities for biological invasions.

Construction of the TGD facilitated the regional spread and establishment of alien species within its 58,000 square-kilometer (km^2) watershed, including the surface of the project's 1080 km^2 reservoir. A recent preliminary survey discovered 55 invasive species in the TGD watershed (Cui 2005), of which the broadleaf fleabane, *Conyza sumatrensis* (Retz.) E. Walker—an aggressive terrestrial invasive plant from the New World—may be the most prominent (figure 5). Water hyacinth, *Eichhornia crassipes* (Mart.) Solms, often hailed as the world's worst invasive plant (Holm et al. 1977), is already widely distributed in the TGD watershed. This floating macrophyte could readily enter the reservoir from numerous nearby rivers, streams, and canals. If water hyacinth covers the reservoir's surface, it could ultimately disrupt hydroelectric power generation by blocking water intake pipes at the dams. Water hyacinth caused such a disruption at the Owen Falls Dam hydroelectric scheme in Uganda in the late 1980s (Kateregga and Sterner 2007).

Alligator weed (*Alternanthera philoxeroides* [Mart.] Griseb.), another of China's major aquatic invaders, can occur in both terrestrial and aquatic habitats (Holm et al. 1977). This species occurs more widely than does water hyacinth in the TGD watershed, and it also poses a threat to hydroelectric power generation. Huge mats of water hyacinth and alligator weed have already periodically blocked waterways in southern China during flooding seasons (figure 6; Ding et al. 1995, Ding and Wang 1998).

The South-to-North Water Diversion Project is intended to alleviate the water shortage in northern China by diverting water from southern China through three south-to-north canals (SNWD 2006). This huge canal project may also become an express route for the dispersal of invasive species, in

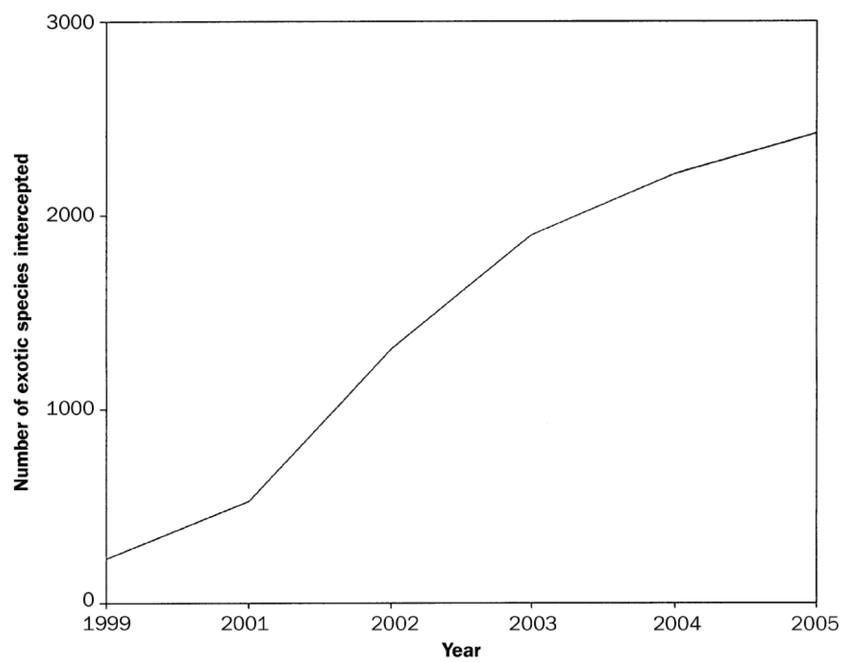

Figure 3. Exotic pest species intercepted in the period 1999–2005: Total number of species intercepted by all border inspections across the country. Data are from Chen and colleagues (2005) and Xia (2004).

particular aquatic and semiaquatic plants. For example, alligator weed, which has infested almost all the southern parts of the canals for more than 20 years (Zhang et al. 2004), could now rapidly spread to central and northern China through these canals. This tropical and subtropical macrophyte (Holm et al. 1977) was initially assumed to be restricted northward at the Yellow River; however, it has recently been discovered along the south bank of the Yellow River (Zhang et al. 2004) and could potentially invade further north.

Expansion of China's rail system westward presents similar environmental hazards. The recently completed Qinghai-Tibet railway links the high Tibetan plateau (> 4000 meters elevation) to the rest of the country through the addition of 1100 km of track (QZTL 2006). Its completion could accelerate the spread of invasive species into what had until recently been a remote region. Goldenrod and common ragweed (*Ambrosia artemisiifolia* L.), both of which are invasive in eastern China (Li and Xie 2002, Dong et al. 2006), and other alien species could spread readily to western China along the rail line to regions where few invasive plants have yet been reported (Liu et al. 2005). Similarly, disturbance caused by construction of the West-East Gas Pipeline Project, which will carry natural gas from Lunnan in Xinjiang to Shanghai by passing through 10 provinces (XHNA 2006), could also facilitate the rapid dispersal of invasive species along the pipeline's 4000-km corridor.

Even well-intended conservation programs might create opportunities for biological invasions, unless the species introduced are carefully evaluated. To foster natural habitat restoration in about 20 provinces, particularly in western regions, China launched a "Grain-to-Green" program in 2000; the program subsidizes farmers with grain and cash to convert cropland to forest or grassland. Upon its expected completion in 2010, approximately 146,700 km^2 of cropland will have been converted (Li 2003). Although traditional Chinese agriculture keeps most crop fields free of insect and plant pests by an almost daily regi-

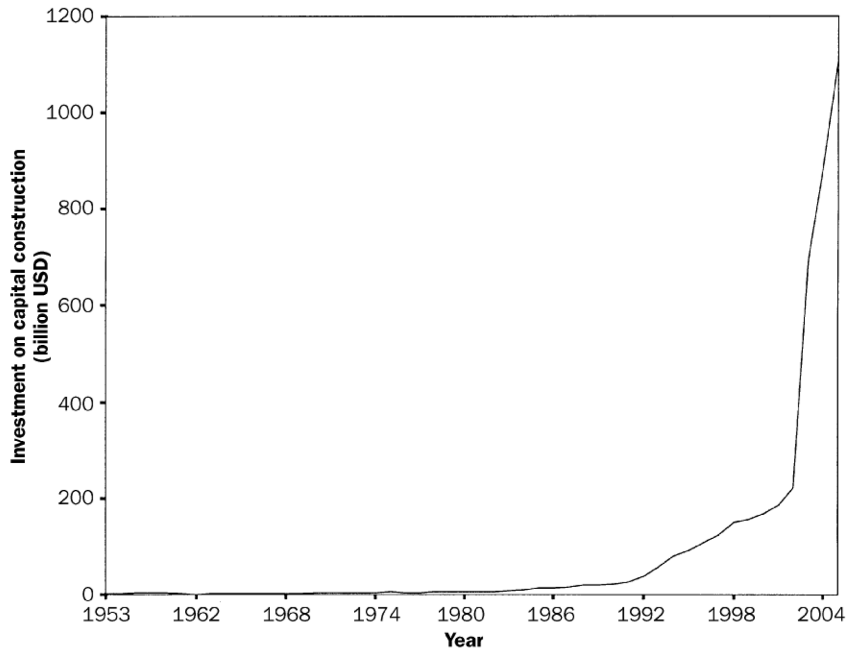

Figure 4. Investment on capital construction in China, 1953–2004. Data are from **China Statistical Yearbook 2005** ***(NBSC 2006).***

Figure 5. An invasive plant, broadleaf fleabane (**Conyza sumatrensis*****), now dominates the flanks of tributaries near the Three Gorges Dam. Disturbance caused by dam construction has provided much new habitat for this plant invader. Photograph: Jialiang Zhang.***

*Figure 6. Vigorous growth by the South American aquatic plant, water hyacinth (*Eichhornia crassipes*), already blocks many canals in south China (Putian, Fujian Province) and will very likely spread further. Photograph: Zhiqun Chen.*

men of weeding and other cultivation, such frequent cultivation is impractical for pest control in forests or grasslands. This radical conversion of land to low maintenance agriculture could greatly increase the introduction and persistence of alien pests such as Crofton weed (*Ageratina adenophora* [Spreng.] R. M. King et H. Rob.) in these newly created habitats. A native of Central America, Crofton weed is considered China's worst invasive plant; it has invaded Yunnan (covering 15% to 20% of 14 counties), Guizhou, Sichuan, and Guangxi provinces in southwest China since the 1940s (NCBDBO 2006). Given the failure to curb the spread of Crofton weed, despite repeated efforts (Wang and Wang 2006), the species' reputation as China's worst invasive plant may be well deserved.

Increased eutrophication exacerbates the growth of aquatic invaders

Booming industrial development has accelerated eutrophication in China's inland waterways and also holds consequences for biological invaders. Nutrients in urban and industrial wastewater, as well as in fertilizer, are increasingly being deposited into freshwater systems (Liu and Diamond 2005), which enhances invasions by introduced aquatic plants. The growth and reproduction of aquatic plants, such as water hyacinth, have been repeatedly correlated with high concentrations of nitrogen and phosphorus in eutrophic freshwater systems (Xie et al. 2004, Zhao et al. 2006). Nutrient enrichment explains in part the emergence of plant invasions in more than 10 lakes or reservoirs and hundreds of rivers and canals in southern China in the last 20 years.

Along with the aforementioned water hyacinth and alligator weed, aquatic invasive species include the South America natives, water lettuce (*Pistia stratiotes* L.) and azolla (*Azolla filiculoides* Lam.), which have been undergoing recent rapid spread, completely covering lakes or rivers in central and southern China (Li and Xie 2002).

Reputedly beneficial species can become invaders

Perceptions of introduced species, especially those deliberately introduced, often change: many species deliberately introduced have become invasive, even as their perceived value has waned (Mack 1991, Lonsdale 1994). Here again, China's rapid economic development has catalyzed the transformation of species once deemed beneficial into invaders. During the l960s to 1970s many local governments actively encouraged farmers to grow water hyacinth, alligator weed, and water lettuce as inexpensive animal fodder (Diao 1990). Since the 1980s, however, these species have been increasingly supplanted by more effective sources of animal feed. With the active cultivation and management of introduced aquatics now largely abandoned, these species have escaped into ponds, rivers, and lakes in Southern China, causing much damage to fisheries, irrigation, and natural ecosystems in as many as 20 provinces (Ding et al. 1995).

Large quantities of grass seed have been imported into China, mostly from the United States, to prevent soil erosion, particularly in western China, and to create lawns in urban areas (CNTVT 2006). About 39,000 kilograms (kg) of grass seed were imported in 1994; this number increased to 3 million kg in 1999 and might now exceed 40 million kg (Xie 2002). Without careful risk assessment and appropriate management, these nonnative grasses could cause unanticipated environmental consequences by competing with native species or exacerbating water shortages (Xie et al. 2001). For example, smooth cordgrass, *Spartina alterniflora* Loisel., native to the Atlantic and Gulf coasts of North America, was introduced into China in 1979 for soil erosion control and coastal dike protection (Wang et al. 2006). It subsequently escaped and became invasive along the eastern Chinese coast. This rapidly spreading perennial grass has altered native communities' composition through competition with native plants, such as Scirpus × mariqueter T. Tang et F. T. Wang at Dongtan on Chongming Island, Shanghai (Chen et al. 2004).

China is also accelerating its intentional introduction of nonnative species other than grasses. In expanding its horticultural industry, China introduced about 150 ornamental plant species (in 120 genera; 30 plant families) between 1997 and 2001 (Xu and Qiang 2004). A field survey from 2001 to 2002 indicated that 11 of these ornamental plant species had already escaped in a Shanghai suburb (Yin et al. 2003).

As part of the goal to create a "2008 Green Olympics," Beijing has taken steps to improve its urban landscape. A total of 60,400 kg of seeds of assorted species and 31,430,000 woody seedlings from other countries were introduced during 2002–2004 across Beijing (Zhang et al. 2006). Even if these nonnative plant species do not themselves become invasive, they might serve as vectors for the entry of nonnative parasites and insects. For example, when fragrant dracaena, *Dracaena fragrans* [L.] Ker-Gawl, was introduced from South America as an ornamental plant in the late 1980s, a serious insect pest, the banana moth (*Opogona sacchari*), was also inadvertently introduced. This insect subsequently invaded 15 provinces, attacking about 50 ornamental and crop plant species (Yin et al. 2006).

With the growth of the Chinese public's interest in more varied pet choices, nonnative fishes, turtles, mice, cockroaches, and other animals have been introduced and dispersed throughout the country (Zhu and Wang 2006). These recently introduced pet species may spread and persist after escaping captivity or being abandoned by their owners. The red-eared slider, *Trachemys scripta elegans* Wied, which is considered among 100 of the "world's worst" invaders (IUCN 2000), has been widely available in pet markets across China in recent years. Many owners abandon or intentionally release these turtles, which have the potential to establish wild populations (Zhu and Wang 2006). Piranhas (*Serrasalmus* spp.) from South America were introduced in the late 1980s and were usually displayed in aquaria because of their fierce predatory reputation. To prevent the potential dangers posed by these aggressive fish escaping into waterways and attacking native aquatic vertebrates, China's central and local governments have ordered their eradication (Zhao et al. 2003).

High stakes for China's environment: Solutions are under way

One consequence of China's rapid economic development is that the diversity and the effects of invasive species are rapidly growing. Although composite losses from 400 known invasive species have yet to be tallied, a preliminary study reports that China's economy may suffer an annual economic loss of about US$14.5 billion because of invasive insects and plants (Gan et al. 2005). With more than 30,000 native species of vascular plants and at least 2340 species of native terrestrial vertebrates (Liu et al. 2003), China is one of the world's hotspots of biodiversity. A burgeoning number of invasive species, as now seen in China, could drastically alter or even replace native communities, decrease biodiversity, and drive some species to extinction (Vitousek et al. 1996).

Although China has begun to recognize biological invasions as severe environmental problems and has provided some funding to support the research and management of these species (Xia 2004), a national campaign against biological invasions is still in its infancy. For most local governments, the prime goal is GDP growth, not environmental protection; invasive species are largely ignored. As in any nation, great efforts will need to be mustered among government agencies to foster awareness—in the economic sector, in the schools, and among the general public—of the costs of invasive species and the benefits of their prevention and control (Lodge et al. 2006). The enactment and strict enforcement of national quarantine regulations are particularly important for preventing the entry of invasive alien species into China and their inland dispersal, as well as for controlling already firmly entrenched invaders in the country. Eradication of a new invasive species is possible only when effective early detection and rapid response systems are in place (Mack and Lonsdale 2002). Worthy goals would include minimizing costly belated campaigns, such as Beijing's current war on the American webworm, and combating new biological invaders at the outset, rather than after they have extracted a heavy economic and environmental toll.

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