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Water Hyacinth in China: A Sustainability Science-Based Management Framework

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Abstract The invasion of water hyacinth (*Eichhornia crassipes*) has resulted in enormous ecological and economic consequences worldwide. Although the spread of this weed in Africa, Australia, and North America has been well documented, its invasion in China is yet to be fully documented. Here we report that since its introduction about seven decades ago, water hyacinth has infested many water bodies across almost half of China's territory, causing a decline of native biodiversity, alteration of ecosystem services, deterioration of aquatic environments, and spread of diseases affecting human health. Water hyacinth infestations have also led to enormous economic losses in China by impeding water flows, paralyzing navigation, and damaging irrigation and hydroelectricity facilities. To effectively control the rampage of water hyacinth in China, we propose a sustainability science-based management framework that explicitly incorporates principles from landscape ecology and Integrated Pest Management. This framework emphasizes multiple-scale long-term monitoring and research, integration among different control techniques, combination of control with utilization, and landscape-level adaptive management. Sustainability science represents a new, transdisciplinary paradigm that integrates scientific research, technological innovation, and socioeconomic development of particular regions. Our proposed management framework is aimed to broaden the currently dominant biological control-centered view in China and to illustrate how sustainability science can be used to guide the research and management of water hyacinth.

Keywords Water hyacinth · Biological invasion · Biodiversity · Environmental management · Sustainability science · China

Biological invasions have become a serious global environmental problem today (Lodge 1993; Mack and others 2000; Normile 2004; Parker and others 1999). Water hyacinth [*Eichhornia crassipes* (Mart.) Solms-Laubach] is one of the most notorious invasive species and has been ranked at the top in the list of the world's worst weeds (Center and others 2002; Howard and Harley 1998). The infestations of water hyacinth in many aquatic systems have reduced native biodiversity, deteriorated ecosystem functioning and services, clogged up lakes and rivers, obstructed navigation, damaged irrigation and hydroelectricity facilities, and resulted in colossal economic losses in many regions of the world. There have been a great number of studies on the invasion of water hyacinth globally, and much experience with controlling the weed, successful and otherwise, has been accumulated. However, the situation of water hyacinth infestations in China, the largest country in the world, is still not clear to the scientific community at large partly because most of the limited number of existing studies have been published in Chinese. Also, the dominant view on water hyacinth management in China seems problematic because it exaggerates the effectiveness of

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biological control while lacking an integrative and transdisciplinary perspective.

Therefore, this artricle provides the first comprehensive overview of the water hyacinth problem in China based primarily on the Chinese literature and our own studies and also proposes a new and broadly based framework for managing water hyacinth by integrating principles and methods in Integrated Pest Management, landscape ecology, and sustainability science.

Biology of Water Hyacinth and Its Invasion in China

Native to the Amazon basin of South America, water hyacinth is a floating plant with extremely high growth rate, and it reproduces itself both asexually through stolons and sexually by seeds (Center and others 2002). Water hyacinth has lavender flowers borne in clusters of up to 23 on a single spike, and the 14-day flowering cycle concludes with seeds released in the water (Barrett 1980; Center and others 2002). A single rosette contains several inflorescences, each of which produces more than 3000 seeds a year (Barrett 1980). The small but long-lived seeds can remain viable in sediments for up to 20 years and can germinate on moist sediments or in warm shallow water (Center and others 2002; Gopal 1987). These remarkable reproductive characteristics allow water hyacinth to spread rapidly in space. For example, in favorable environmental conditions, a single plant can reproduce 140 million daughter plants each year, enough to cover an area of 1.40 km^2 with a fresh biomass of 28,000 tons (Ogutu-Ohwayo and others 1997). Water hyacinth plants can grow higher than 1.5 m above water and form extensive floating mats of interwoven individuals (Howard and Harley 1998). All of these biological attributes make water hyacinth an extremely formidable invasive species.

As an ornamental plant for its beautiful and long-lasting flowers, water hyacinth was introduced to Europe in 1879, Africa (Egypt) between 1879 and 1892 (reaching South Africa around 1910), the United States in 1884, and Australia and Southeast Asia in the early 1900s (Center and others 2002; Howard and Harley 1998; Ogutu-Ohwayo and others 1997). Now it is found in 62 countries on 5 continents between 40° N and 40° S latitudes, resulting in a number of environmental and economic problems worldwide (Center and others 2002; Howard and Harley 1998).

The early history of water hyacinth invasion in China was not well documented. From the limited description found in the Chinese literature, water hyacinth was brought into Taiwan from Japan in 1901 and then from Taiwan to mainland China in the 1930s (Diao 1990; Li and Xie 2002). In the following decades, it began to expand its geographic distribution to the Yangtze River basin and further north (Gu 1991) mainly because farmers cultivated the weed to feed pigs and ducks between the 1950s and 1970s (Fig. 1).

Since the 1980s, as animal fodders have increasingly been provided by compounds from feed mills, water hyacinth has no longer been used as a major food source to feed domestic animals. As a consequence, the weed has rapidly spread into inner rivers and lakes from family ponds, causing widespread agricultural and ecological problems (Yang and Lu 2002). For example, in the Zhu River of Guangdong Province, the daily manual harvesting of water hyacinth increased from 0.5 tons in 1975, to 5 tons in 1985, 50 tons in 1995, and 500 tons in 2000. As of 2006, water hyacinth has infested the water bodies of 19 provinces in China, ranging from the Hainan Island in the south to Shandong Province in the north (Figure 1). Among the most heavily impacted regions are Fujian, Zhejiang, Shanghai, Yunnan, Sichuan, Hunan, Hubei, and Jiangsu.

Environmental and Economic Consequences

Biological invasions are among the greatest threats to biodiversity and ecosystem function, particularly for aquatic systems (Lodge 1993; Howard and Harley 1998; Mack and others 2000; Mooney and Hobbs 2000). A number of studies in the Chinese literature show that water hyacinth infestations have caused serious ecological damages and economic losses in China (Diao 1990; Gao and Li 2004; Gu 1991; Huang and others 2000; Li and Xie 2002; Li and others 2003; Wang 2003; Wu 1993; Xu and others 2003; Yang and others 2002). In general, water hyacinth has reduced native aquatic biodiversity, disrupted food webs and biogeochemical cycles, and deteriorated ecosystem functioning and services of the numerous infested water bodies in China. For example, water hyacinth covers about two-thirds of the water surface of Caohai Lake, which is part of Dianchi Lake of Yunnan Province, resulting in the deterioration of aquatic environment, decline of fish populations, and expansion of breeding grounds for disease vectors such as mosquitoes and flies (Li and others 2003). The number of aquatic plant species declined from 16 in 1960 to 3 in 1990 due largely to water hyacinth invasion (Ding and others 2001; Wu 1993). Known as "the pearl of the plateau," Dianchi Lake is the sixth largest freshwater lake in China, and its infestation by water hyacinth has caused concerns from scientists, policymakers, and local residents.

Water hyacinth also clogs up lakes and rivers, impedes water flows, obstructs navigation, and damages irrigation and hydroelectricity facilities. Boat traffic in Huangpu River in Shanghai is now hindered by water hyacinth mats in fall and winter each year (Gao and Li 2004; Yang and others 2002). About 60% of the water surface of Bailianhe

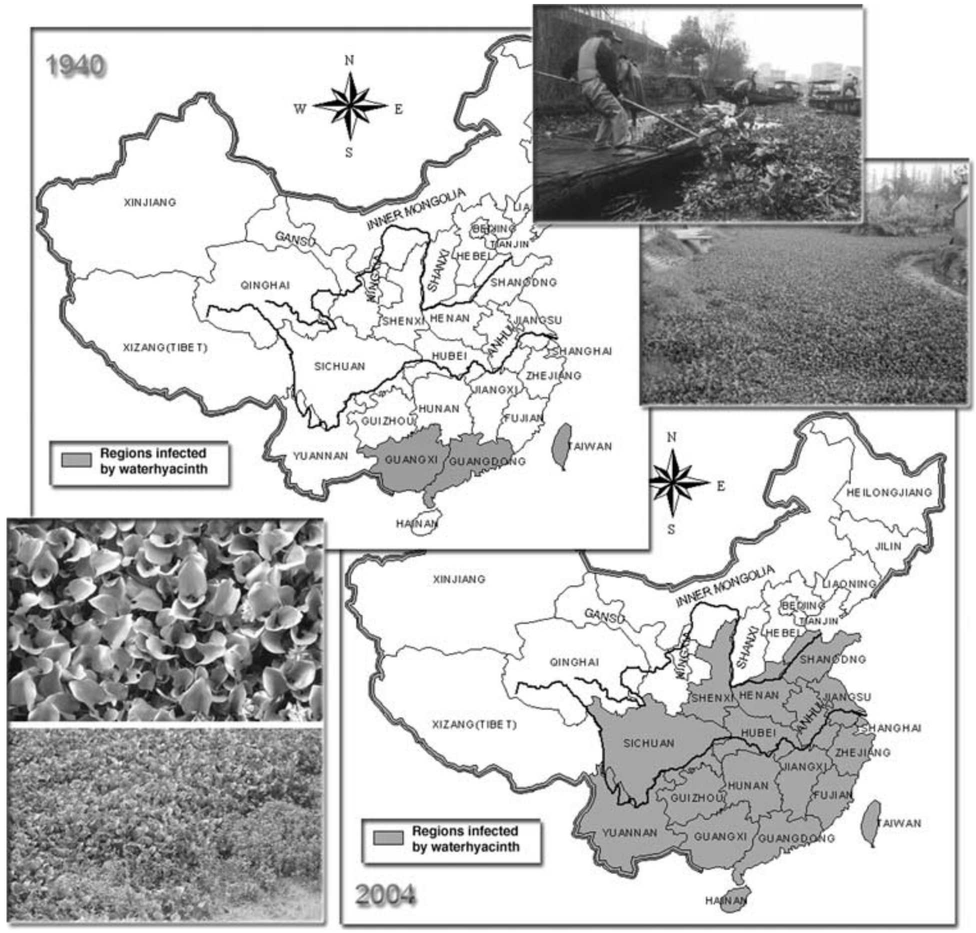

Fig. 1 Provinces of China infested by water hyacinth (*Eichhornia crassipes*). In 1940, water hyacinth was found only in Taiwan, Guangxi, and Guangdong. By 2004, it has infested water bodies of 19 provinces from the Hainan Island in the south to Shandong in the north

Reservoir in Hubei Province is covered by water hyacinth, seriously disrupting its multiple functions of irrigation, flood control, hydroelectric power generation, fishery, navigation, and recreation (Xu and others 2003). Rapid expansion of water hyacinth has greatly impacted navigation and hydroelectric power generation in Shuikou Reservoir of Fujian Province, the largest reservoir in East China. The Grand Canal, the world's earliest and longest canal, has also been infested with water hyacinth. The canal is about 2500 years old and some 1800 km long running from Hangzhou to Beijing. As the major inland waterway, it has made significant contributions to the economic and cultural exchanges between the south and north in Chinese history. The infestation of water hyacinth, along with other kinds of water pollution, now has seriously affected both its ecological waterscape and transportation functionality.

The invasion of water hyacinth has also resulted in serious economic problems in China. For example, in Haining of Zhejiang Province, about 80% of the 35 km^2 of water surface of its 25 rivers is packed with water hyacinth. The local government spent about half a million US dollars each year to manually remove the weed, but this effort was only enough to clean up 60% of the infested areas. Millions of tons of the removed water hyacinth were left untreated, creating environmental hazards such as producing odor and disease-carrying insects (e.g., mosquitoes and flies). In addition, Haining experiences frequent flooding from upper streams between spring and fall. Because water hyacinth has obstructed the two major rivers that release the floodwaters into East China Sea, properties and lives are now subjected to increased danger of flooding. The China Environmental Protection Agency estimated that the total economic loss due to biological invasions in 2000 was about US$ 7 billion, and about 14–17% of this loss was attributed to water hyacinth alone (Wang 2003; Yang and others 2002;). The total cost for water hyacinth control in China is estimated to be more than US$ 12.35 million each year (Li and Xie 2002; Li and others 2003).

Current Situation of Water Hyacinth Control in China

Three control approaches have been practiced worldwide to combat water hyacinth infestations (Howard and Harley 1998; Julien and others 2001): physical removal by hand or machine, chemical control using herbicides, and biological control through natural enemies and pathogens. Physical removal is labor-intensive and only effective on small scales. However, to date, water hyacinth control in China has relied heavily on physical removal, which has proven difficult and costly. Despite the enormous efforts to control the weed, water hyacinth continues to sweep into warm and even relatively cool waters of China. In several reported cases, the removal rate could hardly match the expansion rate of water hyacinth populations (Gao and Li 2004). Chemicals might be instantly effective, but they are often costly and plagued with pollution problems. Thus, chemical control has not been widely adopted in China. Biological control is generally thought to be environmentally safe and of relatively low cost. In 1995, two weevils (*Neochetina eichhorniae* Warner and *N. bruchi* Hustache) were introduced from Argentina and the United States to China, and subsequently contained water hyacinth infestations in Wenzhou of Zhejiang Province (Ding and others 2001; Huang and others 2000). The Chinese literature on water hyacinth seems to suggest that biological control is the most appropriate approach to combating the problem of water hyacinth in China (e.g., Ding and others 2001; Huang and others 2000; Yang and Lu 2002; Yang and others 2002).

Nevertheless, control through biological agents usually does not take immediate effect and will not eradicate the weed. Lu and others (2001) reported that *N. eichhorniae* and *N. bruchi* were successfully established and significantly reduced the abundance of water hyacinth in Wenzhou, Zhejiang Province, but the weevils disappeared from most of the sites 1 year after the introduction. Our own study in Haining, Zhejiang Province (about 280 km north of Wenzhou) has similar results, suggesting that the weevils cannot survive the cold winter in the Yangtze river region (unpublished data). This means that these organisms would have to be reintroduced each year for long-term management purposes. Elsewhere, Schardt (1997) reported that these same beetle species failed to control water hyacinth in Florida of the United States while chemical treatment (with 2,4-D) has been quite successful. Thus, the effectiveness of biological control varies spatially and temporarily with environmental conditions and plant traits (Moran 2004), and its long-term effects on native biodiversity and ecosystem processes are yet to be fully understood. In addition, Messing and Wright (2006) found that certain biological agents have caused negative impacts on non-arget species in some ecosystems. Generalists and vertebrates are more likely to have negative impacts on local environment than specialists and anthropods (Messing and Wright 2006).

A New Strategy for Water Hyacinth Control Based on Landscape Ecology and Sustainability Science

Alhough many have recognized that physical, chemical, and biological controls are all needed in dealing with water hyacinth (Ding 1995; Ding and others 1999, 2001; Gao and Li 2004; Howard and Harley 1998; Jones 2001; Yang and Lu 2002), here we argue that a long-term sustainable management strategy in China should be based on insights from landscape ecology, Integrated Pest Management (IPM), and sustainability science. Landscape ecology is "the science and art of studying and influencing the relationship between spatial pattern and ecological processes across hierarchical levels of biological organization and different scales in space and time" (Wu and Hobbs 2007*;* also see Dale and Haeuber 2001; Turner and others 2001). Sustainability science focuses explicitly on the dynamic interactions between nature and society and integrates science, technology, and socioeconomic development through site-specific, transdisciplinary approaches (Kates and others 2001; Parris and Kates 2003; Wu 2006). The relationship between landscape ecology and sustainability science was discussed in detail in Wu (2006). Our proposed strategy for water hyacinth management in China emphasizes the interactions between spatial pattern and ecological processes and integrates ecological and social processes on different scales, addresses issues of complex adaptive systems and societal learning, and gives emphasis to place-based and problem-driven projects (Figs. 2 and 3).

Specifically, we identify several critical components for this long-term sustainable strategy. First, more efforts are needed to accurately document and monitor the geographic distribution of water hyacinth in China and to understand invasion mechanisms and impacts of land use and global climate change. Both research and monitoring need to consider multiple levels of organizations (household, local community, landscape, region, and nation) and different spatial scales (i.e., local ponds/rivers to networks of water bodies to regional landscapes), a perspective that is reflective of the principles of landscape ecology (Wu and Hobbs 2007; Wu and Loucks 1995). Research and monitoring plans will benefit from following natural boundaries (e.g., watersheds, river basins) instead of administrative units. The relationship between landscape pattern and the spreading process of water hyacinth must be considered at local and regional scales. Technologies such as remote sensing, geographic information systems, and global positioning systems are indispensable. From an ecological perspective, controlling water hyacinth might be considered as "a reverse problem of species conservation," with the goal of intentionally fragmenting its habitats and obliterating its populations.

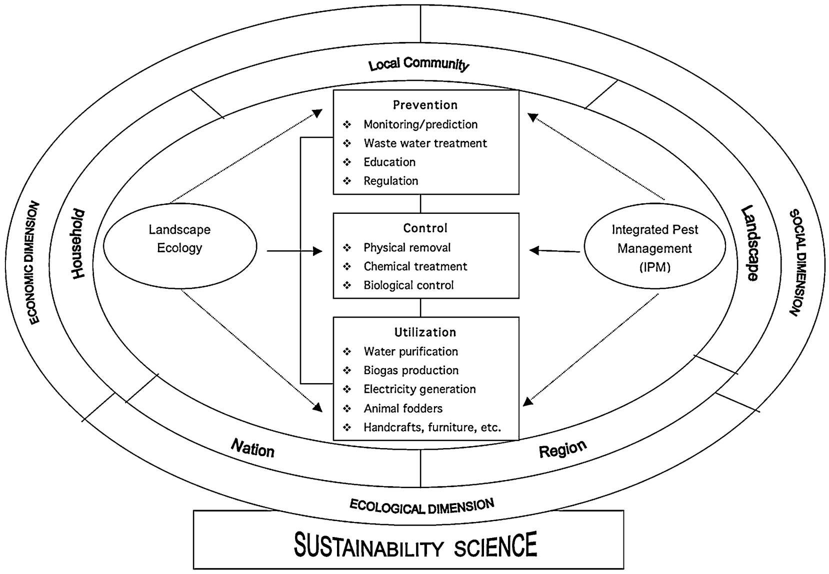

Fig. 2 Illustration of a sustainability science-based management framework for water hyacinth in China that incorporates principles in landscape ecology and IPM

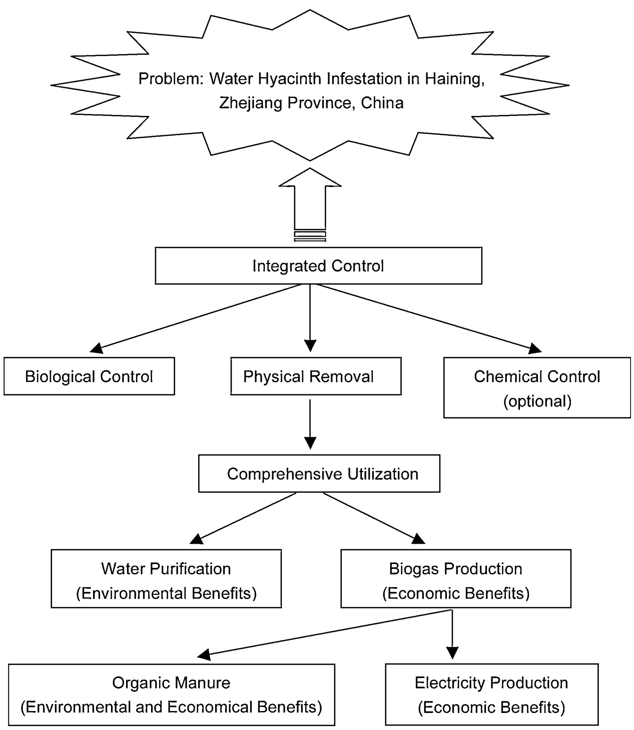

Fig. 3 Illustration of the overall design of a pilot project of applying the sustainability science-based framework in managing water hyacinth in Haining, Zhejiang Province, China

A national-level monitoring and management system needs to be established to coordinate local efforts, provide timely and accurate information on water hyacinth for both researchers and decision-makers, and educate the stakeholders and the general public with updated information and knowledge. Currently, there is a lack of communication between the scientists who study water hyacinth and those who manage it, and a serious discrepancy also exists between national-level policies and local actions on invasive species control. Proactive outreach and communication programs must be created at both local and national levels. Experience gained from studies in other parts of the world, such as South Africa (e.g., van Wilgen 2004), can be useful for achieving this goal.

Second, a systematic IPM approach should be developed, as it maximizes the effectiveness of pest control by combining a variety of techniques such as biological control, manipulating habitats, modifying land-use practices, and careful use of chemicals when necessary (Kogan 1998; Lockwood 2000). Biological control has been recommended as the primary method for controlling water hyacinth in China (Ding and others 2001; Gao and Li 2004; Huang and others 2000), but our own study and others from around the world suggest that a more comprehensive and balanced approach is preferred. Such an IPM approach needs to couple pest control tactics with ecosystem management practices, unite basic with applied sciences, and emphasize prevention measures against the spread of other potential pest species (including those species used as biological control agents). These actions of IPM should be guided by the well-developed theory and principles in landscape ecology (e.g., metapopulation theory, landscape percolation theory, pattern-process-scale principles; see Dale and Haeuber 2001; Turner and others 2001; Wu and Hobbs 2002 for details).

It is necessary to note that there is not a universally accepted definition of IPM, much less a consensus on a set of criteria for its practice (see Cate and Hinckle 1994; Ehler and Bottrell 2000; Kogan 1998; Lockwood 2000; U.S. Congress 1995). Ehler and Bottrell (2000) claimed that there was little "I" in IPM after more than 30 years of research, and that IPM had not been practiced in its really sense within US agriculture to any significant extent. They further pointed out that IPM must emphasize the compatibility and overall effectiveness of different management tactics, rather than simply mixing them. To do so, an IPM practice must explicitly consider both "horizontal integration" (avoiding nontarget effects on organisms on the same trophic levels) and "vertical integration" (balancing the effects of interacting trophic levels such as microbes, plants, insects, and natural enemies of insect pests).

Third, water hyacinth management plans should be multiple-scaled, integrated, and adaptive. The spread of water hyacinth between watersheds or continents is mainly through human activities, whereas its local expansion within a watershed is mostly via asexual reproduction and floating propagules (Howard and Harley 1998). Both prevention and control programs must consider such scale-dependent characteristics of water hyacinth invasions. Whereas earlier efforts have focused primarily on local populations and ecosystems, water hyacinth control must also consider landscape pattern and between-ecosystem interactions. Management plans should anticipate possible influences of land use and global climate change and involve different levels of socioeconomic structures. At the household level, water hyacinth can be collected manually or mechanically and carefully used to produce animal fodders and biogas; at the village or county level, such activities can be enhanced by collective resources and coordination; and at the provincial and national level, appropriate and timely legislations and policies are crucial. In addition, management plans need to be prioritized based on impact measures that consider multiple-scale effects of biological invasions (Parker and others 1999).

Fourth, both control and utilization of water hyacinth should be emphasized as the infestations become spatially contained (Fig. 2). We have carried out a pilot project in Zhejiang to explore the scope and feasibility of integrating control and utilization of water hyacinth following a sustainability science framework (Fig. 3). Water hyacinth, with a C/N ratio of about 15, has a high content of fermentable matter that favors biogas production. Zhou and others (1996) have shown that 1 kg of water hyacinth, when mixed with animal feces, could produce 330 L of biogas through a two-phase anaerobic digestion procedure. To accurately determine the capacity of using water hyacinth for biomass production, we built a large-scale biogas production station near a pig farm in collaboration with the local government of Haining. Our experimental results show that mixing water hyacinth with pig manure can have a much higher biogas production rate than using pig manure alone (unpublished data). Specifically, the biogas production rate was increased by 46% with 15% of water hyacinth mixed with pig manure. Our study demonstrated that 100 kg of water hyacinth material (with about 20% of water) can produce 12 m^3 biogas, which in turn produces 241 kWh of electricity.

Water hyacinth has also been used as a main aquatic plant for water purification in China because of its high capacity of sequestering heavy metals, rare earth elements, and other chemicals (Gao and Li 2004). According to our ongoing experimental research in a duck farm in Zhejiang, water hyacinth was able to effectively purify the heavily eutrophic water of duck-feeding ponds by taking up large amounts of phosphorus and nitrogen as well as suspended particles through its extensive root system (unpublished data). After treatment with water hyacinth, COD (chemical oxygen demand; i.e., the amount of oxygen needed to oxidize organic compounds in water by a standardized test procedure) was reduced by 64.44%. Consequently, water transparency was increased from 9 cm before the treatment to 22.25 cm after the treatment. Similar results were reported elsewhere by Sooknah and Wilkie (2004), who used water hyacinth to treat the polluted water in a dairy farm.

Fifth, water pollution control must be considered an integral part of water hyacinth management on broad scales because polluted water bodies enhance water hyacinth infestations (Gao and Li 2004; Ogutu-Ohwayo and others 1997). China discharges about 41.5 billion tons of wastewater each year, with 47% of its rivers polluted and 65% of its lakes experiencing the problems of eutrophication (Wang 2003). Water hyacinth control must go beyond just the action of killing the weed in local spots, and embrace an integrated landscape management perspective for improving the aquatic environment as a whole.

Conclusion

Studies in the past decades have shown that the scope and severity of environmental and economic impacts of invasive plant species can be enormous. In particular, there have been numerous studies on the spread of water hyacinth in Africa, Australia, and North America. However, the scope and severity of water hyacinth invasion in China have rarely been reported. In this article, we have provided an overview of water hyacinth invasion and its ecological and economic impacts in China, as well as a long-term management framework for controlling water hyacinth infestations based on key principles in IPM, landscape ecology, and the emerging sustainability science. There is a rapidly growing Chinese literature on the invasion of biological species, including water hyacinth, but a comprehensive integrative framework for managing these invasive species is lacking. We hope that our proposed sustainability science-based framework will stimulate the development of broader views on weed management that go beyond the systems in which the invasive species reside and beyond the realm of traditional scientific research. We realize that more efforts are needed to transform this conceptual framework into an operational plan on the ground. However, we also believe that such a comprehensive and integrative framework is a necessary first step toward the sustainable management of invasive species in China and elsewhere. As a new scientific paradigm that focuses on the dynamic society–environment relationship, sustainability science is not only applicable for dealing with problems of biological invasion but also has emerged as a promising enterprise for guiding sustainable development at local, regional, and global scales (Wu 2006).

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