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Recent progresses in mangrove conservation, restoration and research in China

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Abstract

Aims

In this paper, we highlighted some key progresses in mangrove conservation, restoration and research in China during last two decades.

Methods

Based on intensive literature review, we compared the distribution and areas of existing mangroves among selected provinces of China, discussed the issues associated with mangrove conservation and restoration and highlighted major progresses on mangrove research conducted by key institutions or universities in mainland China, Hong Kong, Taiwan and Macao.

Important findings

The population boom and rapid economic developments have greatly reduced mangrove areas in China since 1980s, leaving only 22 700 ha mangroves in mainland China in 2001. Chinese government has launched a series of programs to protect mangroves since 1980s and has established mangrove ecosystems as high-priority areas for improving environmental and living resource management. During last three decades, a total of 34 natural mangrove conservation areas have been established, which accounts for 80% of the total existing mangroves areas in China. Mangrove restoration areas in Mainland China accounted for <7% of the total mangroves areas in 2002. A great deal of research papers on Chinese mangroves has been published in international journals. However, more systematic protection strategies and active restoration measurements are still urgently needed in order to preserve these valuable resources in China.

Keywords:
China • conservation • mangrove • research • restoration

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INTRODUCTION

Mangroves are the characteristic intertidal plants distributed in tropical and subtropical coastlines (Chapman 1976; Lin 1984; Tomlinson 1986). On the global scale, mangrove areas are becoming smaller or fragmented and their long-term survival is at great risk (Duke *et al.* 2007). Mangrove species in China belong to the Indo-Malaysia Northeast subgroup of East group and covered >50 000 ha in 1950s (Lin 1997; Wang and Wang 2007). Before their important ecological and economic values were recognized by Chinese publics in early 1990s, mangroves had been degraded seriously and the areas greatly reduced, with only 22 752 ha remained (Wang and Wang 2007). Issued in 1995, China's Biodiversity Conservation Action Plan included the action plans for marine biodiversity protection in China, which called for increasing mangrove conservation areas. As a result, the majority of natural mangroves have been protected as part of the national wide mangrove nature reserves.

Chinese scientists have conducted a great deal of research on mangroves since 1950s (Lin 1997a). An in-depth review on Chinese mangrove research was conducted by Li and Lee (1997). Since then, increased government investments have greatly improved the research on mangroves in China.

Nearly 1 500 papers have been published in Chinese and international journals since 1990, which provided useful information for the conservation and utilization of mangroves in China. In addition, a series of books about Chinese mangroves were published during last decade (e.g. Chen and Miao 2000; Fan 2000; Liao 2009; Lin 1997; Lin and Fu 1995; Lu and Ye 2006; Tam and Wong 2000; Wang and Wang 2007; Wang *et al.* 2002; Zheng 1999). However, >75% of research papers and most books were written in Chinese, which are not accessible by the international research community. In this paper, we reviewed the rapid developments in the mangrove conservation, restoration and researches in China after 1990s and provide some perspectives and suggestions on future research areas.

MANGROVE CONSERVATION, AFFORESTRATION AND RESTORATION

In China, mangroves distributed naturally in Hainan, Guangdong, Guangxi, Fujian, Hong Kong, Macao and Taiwan (Fig. 1). In 1950s, one mangrove species was successfully transplanted to Yueqing County in Zhejiang Province, where the latitude was ~28°25′N (Zhejiang Forestry Bureau 1961). During the last few decades, the population boom and rapid economic development in agriculture, aquaculture, industry and urban construction have reduced mangrove areas greatly in China. According to the latest survey by State Forestry Administration in 2001 (Table 1), the total mangrove area in mainland China was ~22 000 ha, which was only 44% of that in 1950s (State Forestry Administration 2002). The existing mangrove area in Hong Kong, Macao and Taiwan was ~727 ha in total according to Chen (1997), Leung (1998) and Hsueh and Lee (2000) (Table 1). Thus, the total area of existing mangroves in China was ~22 700 ha in 2001.

Mangrove forests occur mainly in three southern provinces of China (Hainan, Guangdong and Guangxi), which account for 94% of the total mangrove area in China. Among them, Guangdong Province has the largest existing mangroves, followed by Guangxi and Hainan (Table 1). However, mangroves also naturally occupy the intertidal areas of the higher latitudes, such as Fujian Province and Taiwan. In addition, there are some small areas of natural mangroves in Hong Kong and Macao. Although not naturally distributed, there are some mangrove stands in Zhejiang Province, which was transplanted from Fujian during 1950s.

Although accounting only ~0.1% of world mangroves, the mangroves in China have some unique features and important values. Firstly, there are 24 true mangrove species in China, accounting for about one-third of the total true mangrove species worldwide. *Kandelia candel* (L.) Druce, one species in the family of Rhizophoraceae, has long been recognized as a monotypic mangrove genus and occurs in all mangrove distribution zones in China. Recent studies in chromosome number, molecular phylogeography, physiological adaptation and leaf anatomy realized that it should be recognized as *Kandelia obovata* Sheue, Liu and Yong (Sheue *et al.* 2003). Secondly, *K. obovata*, the northernmost distribution species in China, is a good model species for studying mangrove cold resistance and

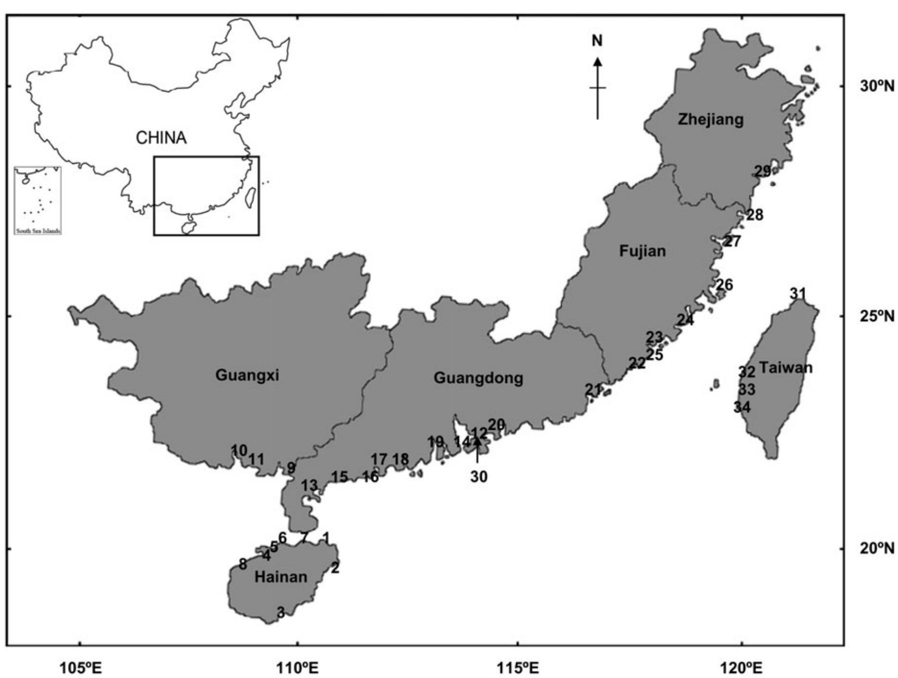

Figure 1: mangrove distribution in the coast along Hainan, Guangxi, Guangdong, Fujian, Zhejiang Provinces, Hong Kong and Taiwan. See Table 1 for the detail names of locations 1–34.

Table 1: surface areas of existing mangroves in China by province

Location	Total existing mangrove area (ha) 2002	Reforestation area[a] (ha) Up to 2002	Restoration area[a] (ha) Up to 2002
Hainan Province	3 930[a]	60	60
Guangdong Province	9 084[a]	672	298
Guangxi Province	8 375[a]	1 093	783
Fujian Province	615[a]	596	369
Zhejiang Province	21[a]	257	21
Hong Kong	380[b]	ND	ND
Macau	60[c]	ND	ND
Taiwan	287[d]	ND	ND
Total	22 752	2 678	1 531

[a] Reports of mangrove resources survey in China, State Forestry Administration (2002)
[b] Chen (1997)
[c] Leung (1998)
[d] Hsueh and Lee (2000); ND = no data.

possible responses to global warming. Thirdly, all true mangrove species in China except *Lumnitzera littorea* can be found in the Qinglan Reserve of Hainan, with a mangrove area of only 1 233 ha (Wang and Wang 2007). Such high species diversity of mangroves is rare in other mangrove regions, which makes the Qinglan Reserve an ideal location for studying the relationship between biodiversity and ecosystem functions. Furthermore, most mangroves in China are distributed in the areas where the population density is among the highest in the world and the local economic growth has increased dramatically during last three decades. Thus, studies and practices in mangrove conservation and restoration in China will provide a good model for other developing countries with similar high intensity of human disturbances to coastal wetlands. Finally, mangroves in China can serve as core components of windshield forests along the coastlines for reducing damage from high frequency of typhoons (State Forestry Administration and State Oceanic Administration 2006).

Mai Po Wetland in Hong Kong is the first mangrove reserve in China, which was established in 1976 and listed as Ramsar Site in 1995 (Li and Lee 1997). Since then, China has made rapid progress in mangrove conservation. Up to date, a total of 34 mangrove nature reserves have been established in different locations of China, and the total protected area was >18 000 ha, accounting for >80% of the mangrove area in China (Table 2). According to the Engineering Programs of Mangroves Conservation and Development in China (2006–16) (State Forestry Administration and State Oceanic Administration 2006), more mangrove natural reserves will be established in the coming decades.

In addition to the establishment of mangrove natural reserves, Chinese government has made great efforts in mangrove reforestation since the early 1990s (Zheng *et al.* 2003). Up to 2002, ~2 678 ha mangroves have been replanted, while only 57% of them were successful restored (Table 1). According to the statistics conducted by State Forestry Administration and State Oceanic Administration (2006), there are ~65 600 ha of intertidal zones suitable for mangrove afforestration in China, indicating great potential for the expansion of mangrove areas by silviculture.

ISSUES ASSOCIATED WITH MANGROVE CONSERVATION AND RESTORATION

Despite of the apparent success in mangrove conservation and reforestation during last two decades, there are still many threats to Chinese mangroves. Urban and aquaculture wastewater discharge (Wang *et al.* 2002), oil pollution (Liu *et al.* 2006; Wang *et al.* 2002), biological invasion (Lin 2003; Wang *et al.* 2002), insect outbreak (Jia *et al.* 2001a, 2001b; Qiang and Lin 2004) and the influence of water transportation (Wang and Wang 2007; Wang *et al.* 2002) remain serious threats to mangroves in China. For a long period of time, wastewater from the upstream and landfill pollution discharged directly into the mangrove wetland without proper treatments, which were popular in the coastlines of Southern China (Lin 1997). Although the self-purification functions of mangrove wetlands were reported (Dwivedi and Padmakumar 1983; Huang *et al.* 2000; Tam and Wong 1995; Wong *et al.* 1997), pollution still adversely changed the ecosystem functions and the biodiversity of the mangrove ecosystem (Wang *et al.* 2002). For example, the quantities and densities of benthic animals, birds or fishes declined in several polluted mangrove forests (Cai *et al.* 2000; Lin *et al.* 2007; Ma *et al.* 2003; Wang *et al.* 2002).

Biological invasion is a global problem for its great threats to native species and local ecosystems (Drake *et al.* 1989; Higgins and Richardson 1996), which is also common to the mangroves in China. For example, *Spartina alterniflora,* a C_4 grass native to the east coast of USA and was first introduced to Fujian Province in China as a windproof and beach-protecting plant. Because of its significant roles for these purposes, this species was later planted in large areas in other provinces, such as Jiangsu, Zhejiang and Guangdong. By 2000, the coverage of *S. alterniflora* was >112 000 ha in China (Zhu and Qin 2003). The strong dispersal and reproductive capacities of the seeds or new ramets from rhizome segments of *S. alterniflora* made it a very invasive species, which has brought serious threats to the native mangroves (Qian and Ma 1995). For example, >167 ha of *S. alterniflora* were found in Shankou mangrove nature reserve in 2005 and most of the mangrove tidal flats in Qi'ao mangrove nature reserve were covered entirely by *S. alterniflora* now. The *S. alterniflora* invasion caused hundred millions of dollar loss per year in China (Chen 1998; Chen *et al.* 2004b). For example, >100 million ¥ lost in the aquaculture was reported each year along in the six counties in Fujian Province (Li and Xie 2002). Several control methods have been developed to prevent and mitigate the spread of *S. alterniflora,* including burning, harvesting, herbicide application, freshwater flooding and replacement with an exotic

Table 2: **detail information for current mangrove natural reserves in China (Up to 2007)**

No.[a]	Name of reserve	Location	Conservation area (ha)	Mangrove area (ha)	Time of established	Class	No. of mangrove species[b]
Hainan Province							
1	Dongzhai Harbor, Haikou	19°54′N, 110°20′E	3 337	1 733	1980	National[c]	14 + 9
2	Qinglan Harbor, Wenchang	19°34′N, 110°45′E	2 948	1 233.3	1981	Provincial	23 + 12
3	Sanya	18°11′N, 109°33′E	923.5	59.7	1989	Local	18 + 9
4	Xinying, Danzhou	19°44′N, 109°16′N	115	79.1	1992	Local	10 + 6
5	Dongchang, Danzhou	19°51′N, 109°33′E	696	478.4	1986	Local	ND
6	Xinying, Lingao	19°51′N, 109°33′E	67	ND	1983	Local	7 + 5
7	Huachang Bay, Chengmai	19°54′N, 109°57′E	150	150	1995	Local	7 + 5
8	Dongfang	19°14′N, 108°39′E	1 429	123.6	2006	Local	ND
Guangxi Province							
9	Shankou, Hepu	21°28′N, 109°43′E	8 000	806.2	1990	National[c]	9 + 6
10	Beilunhe, Fangchenggang	21°30′N, 108°09′E	2 680	1 131.3	2000	National[c]	10 + 8
11	Maowei Bay, Qinzhou	21°43′N, 118°38′E	2 784	1 892.7	2005	Provincial	8 + 7
Guangdong Province							
12	Futian-Neilingding, Shenzhen	22°32′N, 114°05′E	921.6	70.0	1984	National	5 + 7
13	Zhanjiang	20°15′-21°55′N, 109°40′-110 °55′E	20 278.8	7 256.5	1997	National[c]	10 + 9
14	Qi'ao-Dangan Island, Zhuhai	22°26′N, 113°38′E	7 363	193.3	2000	Provincial	8 + 7
15	Shuidong Bay, Maoming	21°29′N, 111°03′E	1 950.0	150.9	1999	Local	ND
16	Chengcun, Yangxi	21°45′N, 111°44′E	1 320.0	ND	ND	Local	ND
17	Yangjiang, Yangxi	21°42′N, 111°55′E	1 060.0	ND	2000	Local	ND
18	Zhenhai Bay, Enping	22°00′N, 112°22′E	666.7	134.3	2000	Local	ND
19	Jiangmen	22°13′N, 113°05′E	520	133	2004	Local	10 + 7
20	Huidong, Huizhou	22°48′N, 114°48′E	533.3	136	2000	Local	8 + 3
21	Shantou	23°18′N, 116°45′E	10 333.3	1 644.6	2001	Local	2 + 1
Fujian							
22	Zhangjiang Estuary, Yunxiao	23°54′N, 117°27′E	2 360	83.3	1997	National[c]	7 + 3
23	Jiulongjiang Estuary, Longhai	24°26′N, 117°54′E	600	197.3	1988	Provincial	4 + 2
24	Quanzhou Bay, Quanzhou	24°47′N, 118°38′E	7 039	17	2003	Provincial	3 + 2
25	Xiamei, Zhangpu	23°58′N, 117°42′E	400	ND	1997	Local	ND
26	Changle, Fuzhou	26°01′N, 119°38′E	2 921	34.3	2003	Local	1 + 1
27	Sandu Bay, Ningde	26°41′N, 119°46′E	39 981	ND	1997	Local	1 + 1
28	Shacheng Harbor, Fuding	27°16′N, 120°18′E	2 174	7	1997	Local	1 + 0
Zhejiang							
29	Yueqing	28°20′N, 121°10′E	2 000	21.5	2005	Local	1 + 0
Hong Kong							
30	Mai Po	22°30′N, 114°02′E	380	120	1976	National[c]	8 + 7
Taiwan							
31	Tanshui, Taibei	25°09′N, 121°26′E	190	77.8	1986	Local	1 + 1
32	Haomeiliao, Chiayi	23°22′N, 121°07′E	1 171	31.7	1987	Local	2 + 1
33	Peimeng, Tainan	23° 16′N, 120°06′E	2 447	28.5	1987	Local	2 + 0
34	Sutsao, Tainan	23°02′N, 120°07′E	547	8.7	1994	Local	4 + 1
	Total			>18 033			

[a] The numbers are denoted to the location number in Figure 1,
[b] mangrove species is shown as true mangrove species + semi-mangrove species; the classification of true mangrove species and semi-mangrove species follows Wang and Wang (2007). *Excoecaria agallocha* belongs to true mangrove species (Wang and Wang 2007) and
[c] listed as Ramsar Wetland; ND = no data and local = county level or city level (Hsueh 1995; State Oceanic Administration 1996; Lin 1997a; Lin and Fu 2005; Zhang and Sui 2001; Chen *et al.* 2001; State Forestry Administration and State Oceanic Administration 2006).

fast-growing mangrove species, *Sonneratia apetala* (An *et al.* 2007; Lin 1997; Liu and Huang 2000; Tang *et al.* 2007). However, the effectiveness of all these methods appears to be very limited since the invasion of this exotic grass occurred in more areas during last few years.

On the other hand, there are still some great challenges in replanting mangroves on locations where mangroves have been destroyed. First, the survival rates in mangrove afforestation are quite low. As reported by State Forestry Administration (2002), the survival rate of replanting mangroves in Guangdong Province was <44% in 2001. Environmental factors, such as tidal inundation periods, seawater salinity and air temperature can affect the survival rate of mangrove reforestation. Selecting suitable tidal zones for mangrove replantion (i.e. the plantable tidal flats, which refer to the tidal flats where natural mangroves distributed and the planted mangrove seedlings can survive (Zhang *et al.* 1997)) is essential in any mangrove restoration project (Chen *et al.* 2004a). In Panyu County, Guangdong Province, for example, ~90% of the replanting mangrove seedlings survived in the plantable tidal flats, but >80% of those planted in the tidal flats of 0.8 m's lower than the plantable tidal zone died after 12–15 months (Chen *et al.* 2001). In the areas with higher latitude, such as Fuding in Fujian (27°20′N) and Yueqing in Zhejiang (28°15′N), low air temperature (−2.2 to −4.2°C) in winter is a major threat to the survival of mangrove seedlings. Only 20 ha of the total 256-ha planted mangroves survived in Zhejiang during the period from 1980 to 2001 (Table 1), which was mainly due to the relatively low air temperature in the winters.

Secondly, mono-species or exotic species are often used in the mangrove reforestation in China, which reduces the biodiversity of replanted forests. Although it has long been known that reduced biodiversity is sensitive to be easily subjected to insect outbreak and has low ecological values, a few species of native mangroves (*K. obovata*, *Sonneratia caseolaris*, *Rhizophora stylosa*) were frequently planted in monoculture for most of the reforestation projects. This is because most of these reforestation projects are aimed mainly for the appearance of the planted trees and for the high survival rates. On the other hand, some fast-growing exotic mangrove species were introduced and intensively used in many mangrove afforestation projects in China during last two decades (Liao *et al.* 2003; Wang *et al.* 2002). For example, *S. apetala* from Bangladesh were planted in many locations along the coastline of Southern China, such as the Dongzhaigang Mangrove Nature Reserve of Hainan, the Zhanjiang, Qi'ao and Futian Mangrove Nature Reserves of Guangdong, Beilunhe Mangrove Nature Reserve of Guangxi and several locations in Fujian. The total area of *S. apetala* forests was estimated as ~3 800 ha (Li and Liao 2008), about half of the total replanted mangrove areas so far. Ironically, *S. apetala* was also used to control the invasive *S. alterniflora* (Tang *et al.* 2007), even though the invasiveness of this exotic mangrove species was not yet fully studied (Chen *et al.* 2008b). It may be a good strategy to control invasive grasses using fast-growing pioneer mangroves such as *S. apetala* and then the exotic mangroves are replaced with native species. However, more studies are needed to test this approach before it is implemented at large scale.

PROGRESSES ON MANGROVE RESEARCH

Mangrove research in China began in early 1950s and has been well developed during last five decades (Lin 1997). Early work focused mainly on mangrove floristics (He 1951), taxonomy (Hou and He 1953), population ecology (He 1957), community and vegetation distributions (He 1957; Zhang *et al.* 1957). The research progresses on Chinese mangroves before 1990 were reviewed by Li and Lee (1997). Since then, significant amount of books and scientific papers have been published, indicating the rapid development in this research field. In total, there were 1 473 papers published in domestic and international journals from 1990 to 2007, according to the records in the Weipu Database of China and the Web of Science Database (Table 3). The number of officially published papers on Chinese mangrove (included in mainland China, Hong Kong, Macao and Taiwan) since 2000 was >2-fold of that during 1990–99 (Table 3). In fact, the number of annual published papers on mangroves by Chinese scientists increased exponentially from 1990 to 2007 (Fig. 2). The proportion of the peer review journal papers written by Chinese scientists to the world mangrove publications after 2000 was 10.2%, which was lower than that in 1990s (Table 3). Although research papers published by Chinese scientists were double after 2000, the world mangrove researches developed more rapidly based on the total number of published Science Citation Index (SCI) papers.

Between 1990 and 2007, the mangrove research in China focused on a dozen areas (Fig. 3), which included remote sense and modeling, aquaculture, global ecology, geography and hydrography, energy flow, morphology and anatomy, molecular ecology, pharmaceutics and active material exploitation, silviculture, community and population ecology, biodiversity, pollution ecology, ecophysiology, conservation and management. Among them, five research areas increased most rapidly, including molecular ecology, pollution ecology, biodiversity, conservation and management, silviculture and pharmaceutics and active material exploitation.

Extensive researches on mangrove ecosystem structure and function revealed extremely high biomass and primary production for the mangrove forests in China. The highest biomass among Chinese mangrove forests was found in the *Bruguiera sexangula* forest in Dongzhai Nature Reserve of Hainan, with the biomass of 248.5 t/ha, followed by the *R. stylosa* forest in Shankou nature reserve in Guangxi (196.2 t/ha) and the *K. obovata* forest in Hong Kong (129.6 t/ha) (Lin *et al.* 1990, 1992; Lee 1990). High litter production and litter decomposition rates were also found in the Chinese mangrove communities (Fan and Lin 1995; Lin and Fan 1992; Yin and Lin 1992). Based on these results, a ''Three-High'' or ''3-H'' theory on mangrove

Table 3: number of papers on China's mangroves published from 1990 to 2007. Officially published papers of Mainland China, Hong Kong, Taiwan and Macao mangroves were included. Abstracts submitted to conferences and book chapters were not included

Year	No. of publications in Weipu database of domestic journals in Mainland China	No. of publications in SCI journals of Web of Science database	Total No. of world mangrove publications in SCI journals of Web of Science database	Proportion of China's SCI publications to world mangrove publications (%)
1990–99	307	104	679	15.3
2000–07	780	282	2 752	10.2
Total (1990–2007)	1 087	386	3 431	11.3

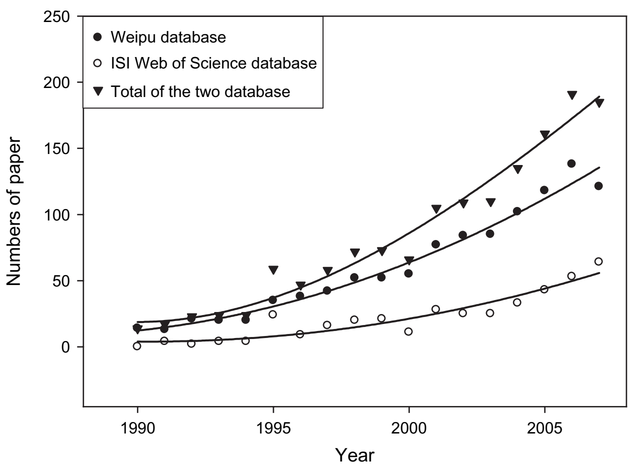

Figure 2: number of papers on China's mangroves from Weipu database and ISI Web of Science database from 1990 to 2007, including Mainland China, Hong Kong, Macau and Taiwan. These papers do not include abstracts submitted to conferences.

communities, i.e. high productivity, high return ratio and high decomposition ratio, was later proposed (Lin 1997).

There were increasing interests in studies on the interactions between Chinese mangrove ecosystems and global change. However, so far the work focused mainly on methane dynamics in mangrove wetlands (Lu *et al.* 1999; Ye *et al.* 1997) and the responses of mangroves to tidal flooding associated with sea level rise (e.g. Ye *et al.* 2003, 2004). Little is known about how mangroves and their ecosystems in China respond to elevated CO_2, global warming or nitrogen deposition. In China, sea walls were constructed in many locations along the coastline to prevent damages from frequent typhoons and hide tides, which not only increased the difficulty in mangrove reforestation (Fan 1995) but also limited mangrove landward migration in response to sea level rise. Thus, more studies in this field are urgently needed to assess potential impact of global change on the mangroves in China. Long-term ecological research stations are now established in Hainan's Donzhaigang Mangrove Nature Reserve (Liao 2009), Guanngdong's Zhanjiang Mangrove Reserve and Fujian Zhangjiangkou Mangrove Reserve (by our group), which will greatly enhance this field research in the coming decades.

A great deal of field and greenhouse studies pointed to great challenges in selecting plantable tidal flats for the mangrove afforestation efforts in China (Fan and Li 1997; Mo and Fan 2001). According to Zhang *et al.* (1997), mangrove can only occupy the tidal flats between the mean sea level (of slightly above) and the highest tidal level in the tropical region. Plantable tidal flats for *K. obovata* have been established for Guangxi (Mo *et al.* 1995), Shenzhen (Liao *et al.* 1997a) and Xiamen (Chen *et al.* 2006). Physiological studies showed that *B. gymnorrhiza* had lower tolerance to soil flooding than *K. obovata* (Ye *et al.* 2003), while the optimal tidal inundation period for *K. obovata* growth and photosynthesis was 2–4 hr per tidal cycle (Chen *et al.* 2004a, 2005). Studies on mangrove management and new techniques in silviculture developed rapidly after 2000 (Fig. 3). The exotic *S. apetala* was shown to have good tolerance of high tide and chilling conditions (Li *et al.* 1997; Liao *et al.* 2004), which may explain why it was considered as one of the best mangrove afforestation species and used almost in all mangrove afforestation projects in China.

Researches on the potentials of mangrove wetlands for wastewater treatments and pollutant degradation have been also greatly promoted in China since 1990s. Mangrove wetland was regarded as an effective ecological system for the removal of nutrients and other anthropogenic pollutants (Tam and Wong 1997; Wong *et al.* 1997). More than 70% of dissolved organic carbon, ammonia and total Kjeldahl nitrogen and ~50% of inorganic nitrogen could be removed by a constructed wetland of *K. ovobata* in a greenhouse study in Hong Kong (Wu *et al.* 2008a). Using a constructed wetland in Futian Mangrove Nature Reserve in Guangdong, Yang *et al.* (2008) found higher treatment efficiencies of *Aegiceras corniculatum* and *S. caseolaris* communities for sewage wastewater than the *K. obovata* communities. Furthermore, the bacterial consortium enriched in mangrove sediments was also shown to be very effective in facilitating the degradation of many polycyclic aromatic hydrocarbons (Luan *et al.* 2006; Zhong *et al.* 2007).

Medicinal applications of Chinese mangrove plants were known for a long period of time (Lin and Fu 1995), which stimulated great interests in the studies on the sources, compound structures and bioactivities of natural products from mangrove materials after 2000 (Wu *et al.* 2008b). Several natural products, such as xylocarpins A and B and scyphiphorins A and B, were isolated from the fruits and seeds of *Xylocarpus granatum* and *Scyphiphora hydrophyllacea*, and their configurations and bioactivities were fully evaluated (Li *et al.* 2007; Tao *et al.* 2007; Wu *et al.* 2008c). *Ceriops tagal* was another mangrove

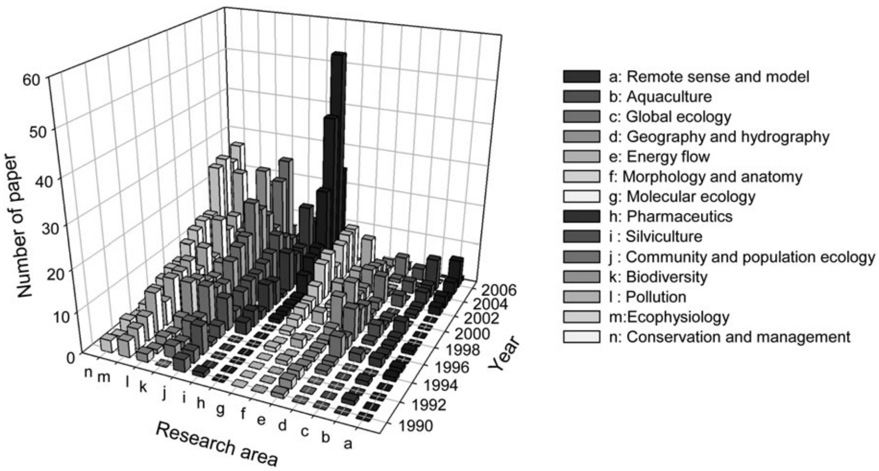

Figure 3: distribution of published papers in 14 major research areas from 1990 to 2007.

species with high medicinal values and three new dimeric diterpenes have been isolated from its roots recently (Chen *et al.* 2008a). However, the direct utilization of mangrove materials for medicine production will likely reduce mangrove resources and should be avoided. A better way for this application is to formulate new medicines through chemical synthesis base on the compound configurations of related compounds found in certain mangrove materials.

In the field of molecular ecology, great progresses have been made since 2000, especially in the areas on the geographical distances and species relationships of Chinese mangroves. The genomic basis of the adaptive evolution and speciation in mangrove was established (Zhong *et al.* 2002; Shi *et al.* 2005; Zhou *et al.* 2007), and several molecular biomarker, including chloroplast DNA, mitochondrial DNA and inter-simple sequence repeat, were used to identify the gene flows between South China Sea and nearby regions (Ge and Sun 2001; Su *et al.* 2006, 2007; Tan *et al.* 2005). Molecular markers were also used as taxonomic evidences for several mangrove species classifications (Qiu *et al.* 2008; Zhou *et al.* 2005). For example, two *Sonneratia* species in Hainan Province, *Sonneratia* × *hainanensis* and *Sonneratia* × *gulngai*, have been speculated as natural hybrids derived from hybridization between *Sonneratia alba* and *Sonneratia ovata* and *Sonneratia alba* and *Sonneratia caseolaris*, respectively (Duke 1984; Wang *et al.* 1999), but a recent molecular study suggested that they were not true hybrid species (Zhou *et al.* 2005). These studies illustrated the values of using modern technologies in resolving long-standing ecological or evolutionary issues in mangroves.

FUTURE PERSPECTIVES

Over the past two decades, a large number of case studies have significantly increased our understanding of the structure and function of the mangrove ecosystems as well as the values of mangroves. However, there are still many areas needed to be strengthened in the future.

Firstly, although mangrove ecosystem functions in China have been studied intensively, which mangrove species is the key stone species of Chinese mangrove ecosystems is still not resolved. More controlled experiments on the relationships between species diversity and ecosystem functions of mangroves should be conducted to resolve this issue.

Secondly, many studies showed that mangroves would migrate landward and expand laterally into areas of higher elevations in response to sea level rise (see review by Gilman *et al.* 2007). As pointed out earlier, the construction of sea walls, plus many skyscrapers behind natural mangrove wetlands, may prevent such migration from occurring, so we need to evaluate the fate of mangroves in China under rising sea levels in coming decades or century.

Thirdly, biological invasions such as those of *S. alterniflora* may jeopardize mangrove habitats. We still lack good understandings of their invasive mechanisms and the efficient measures for controlling such invasions. More field and greenhouse studies are needed in this field.

Fourthly, great efforts and achievements have been made in mangrove afforestation restoration in China, but there is still a lack of a universal standard system for evaluating such efforts and achievements. Collaborations among governmental agencies (such as State Administration of Forestry), research institutions and local communities are strongly encouraged in establishing such evaluation standard system for mangrove afforestation and restoration.

Finally, cooperation among related mangrove research institutions in mainland China, Hong Kong and Taiwan is essential to ensure more successful conservation, restoration and research of mangroves in China. There has been continuous cooperation on mangrove researches between mainland China and Hong Kong since 1990s, but collaboration between mainland China and Taiwan just began recently. We recognize that restoring and protecting mangrove wetlands in all three areas of China require collaborative efforts from all parties.

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