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Review

Insecticide resistance in vector mosquitoes in China

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Abstract: Because of their special behaviour, physiology and close relationship with humans, mosquitoes act as one of the most important vectors of human diseases, such as filariasis, Japanese encephalitis, dengue and malaria. The major vector mosquitoes are members of the *Culex, Aedes* and *Anopheles* genera. Insecticides play important roles in agricultural production and public health, especially in a country with a huge human population, like China. Large quantities of four classes of insecticides, organochlorines, organophosphates, carbamates and pyrethroids, are applied annually to fields or indoors in China, directly or indirectly bringing heavy selection pressure on vector populations. The seven major species of vector mosquito in China are the *Culex pipiens* L. complex, *C. tritaeniorhynchus* Giles, *Anopheles sinensis* Wied., *A. minimus* Theobald, *A. anthropophagus* Xu & Feng, *Aedes albopictus* (Skuse) and *Ae. aegypti* L., and all have evolved resistance to all the above types of insecticide except the carbamates. The degree of resistance varies among mosquito species, insecticide classes and regions. This review summarizes the resistance status of these important vector mosquitoes, according to data reported since the 1990s, in order to improve resistance management and epidemic disease control, and to communicate this information from China to the wider community.

Keywords: vector mosquitoes; chemical insecticides; resistance monitoring; vector control

1 INTRODUCTION

Insecticides play a central role in controlling major vectors of diseases such as mosquitoes, sandflies, fleas, lice, tsetse-flies and triatomid bugs.[1] Some insects are able to survive a wide variety of physical and biological conditions owing to their enormous reproductive capacity and genetic flexibility. Resistance to insecticides by insects is considered to be a recent evolutionary adaptation to environmental changes, occurring in less than one century in response to sequential applications of chemical insecticides, organochlorines, organophosphates (OPs), carbamates and pyrethroids, and even biological insecticides. The emergence and increase of resistance problems not only shortens the lifespan of currently available insecticides but also undermines the efficacy of newly discovered or developed insecticides owing to cross-resistance and multiple resistance mechanisms.

Owing to its special behaviour, physiology and close relationship with humans, the mosquito acts as one of the most important vectors of some human diseases. The major vectors are members of the *Culex, Aedes* and *Anopheles* genera. *Culex* is the major vector of filariasis, Japanese encephalitis and West Nile virus, *Aedes* the major vector of dengue and dengue hemorrhagic fever and *Anopheles* the major vector of malaria.[1] The control of malaria in Africa, where over 90% of the world's cases occur, has been the focus of the WHO over tens of years.[2] With the prevalence and severity of resistance to DDT in several *Anopheles* species, pyrethroids remain the only insecticides authorized by the WHO for extensive use on nets in Africa's mosquito control campaigns.[3] However, the current large-scale presence of pyrethroid resistance in mosquitoes in West Africa will affect control efforts, and selection of multi-resistance mechanisms in both East and West Africa through exposure to DDT and pyrethroids may result in widespread failure of this strategy.[2]

Since 1997, insecticide production in China has been over 3.9×10^8 kg, and application around 2.5×10^8 kg per annum.[4] It is hardly surprising, therefore, that insects have readily developed resistance. The present review summarizes the resistance status of important vector mosquitoes in China, using data reported since the 1990s. The aim is to improve resistance management and epidemic disease control, and to act as a window for the world to know about this information from China.

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2 CHEMICAL CONTROL AND RESISTANCE MONITORING OF VECTOR MOSQUITOES IN CHINA

There are more than 3000 mosquito species in the world, among which over 300 species have been found in China. In China, large quantities of chemical insecticides have been used to control mosquitoes since the mid-1950s, and mosquitoes have sequentially become resistant to organochlorines, organophosphates and pyrethroids.[5]

The important vector mosquitoes in China are the *Culex pipiens* L. complex, *C. tritaeniorhynchus* Giles, *Anopheles sinensis* Wied., *A. minimus* Theobald, *A. anthropophagus* Xu & Feng, *Aedes albopictus* (Skuse) and *Ae. aegypti* L. The most widely distributed and extensively investigated are the *C. pipiens* complex and *A. sinensis*, and the areas where vector insecticide resistance monitoring has been carried out since the 1990s are located mainly in the eastern and southern provinces (Fig. 1). Suitable natural conditions, frequent epidemics and a prosperous economy in these areas have encouraged heavy use of insecticides and resistance investigation. In contrast, low mosquito abundance, little spread of epidemic diseases and slow economic development account for the few reports from other areas, especially from the north-western provinces (Fig. 1).

Resistance is commonly monitored by bioassay, by determining LC_{50} (50% lethal concentration) or by using uniform diagnostic doses. When the LC_{50} is measured for populations, usually a high resistance level (H) is defined as a resistance ratio (LC_{50} of field population divided by LC_{50} of susceptible strain) greater than 20, a moderate resistance level (M) is defined as a resistance ratio between 10 and 20 and a low resistance level (L) is defined as a resistance ratio between 2 and 10, and less than twice that of the susceptible strain is defined as susceptibile (S).

The use of diagnostic doses was initiated and standardized by the WHO in the mid-1980s. Some criteria were modified in 1992 for better service in Chinese cases (Table 1).[6] The designation of resistance levels in this system is different from the LC_{50} system. Obvious resistance (R^*) is when death is less than 80% of that under the diagnosis dose, elementary resistance ($M^\star$) is when death is between 80% and 99% and susceptibility (S^*) is when death is greater than 99%.[6] Other methods, such as biochemical, immunological and molecular

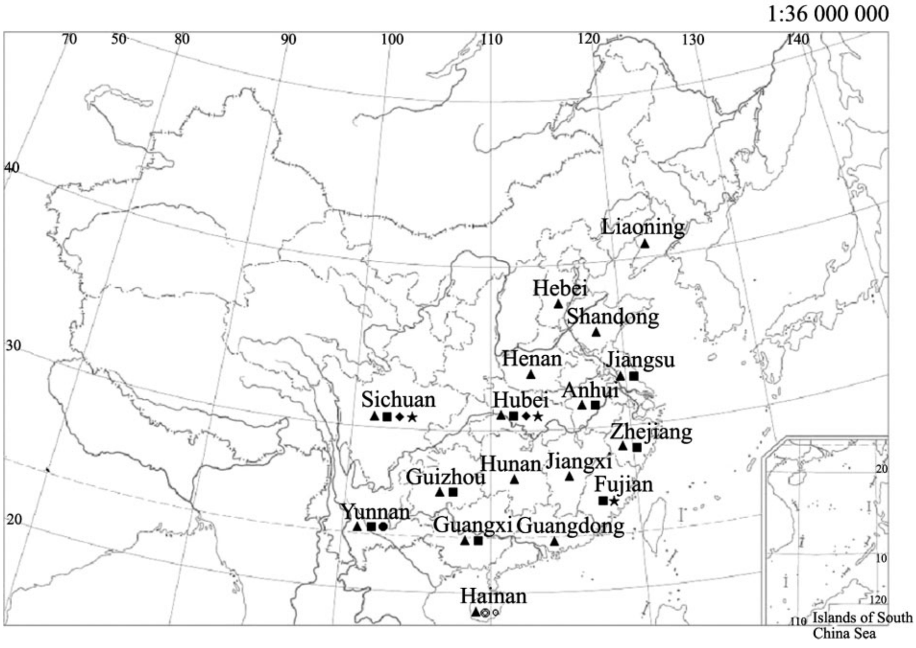

Figure 1. Regional distributions of insecticide resistance monitoring of seven species of vector mosquito in China since 1990: ▲, *Culex. pipiens* complex; ■, *Anopheles sinensis*; ⧫, *C. tritaeniorhynchus*; ●, *A. minimus*; ★, *A. anthropophagus*; ◎, *Aedes albopictus*; ⦿, *Ae. aegypti*.

Table 1. Diagnostic doses for monitoring mosquito insecticide resistance in China

Species	DDT	Malathion	DDVP	Fenitrothion	Permethrin	Deltamethrin
A. sinensis (adults)	4%, 1 h	3.2%, 1 h	–	1%, 1 h	0.2%, 1 h	0.01%, 30 min
A. anthropophagus (adults)	4%, 1 h	3.2%, 1 h	–	–	0.2%, 1 h	0.01%, 30 min
A. minimus (adults)	4%, 1 h	3.2%, 1 h	–	1%, 1 h	0.2%, 1 h	0.01%, 30 min
C. pipiens (larvae)	$0.05\ mg\ L^{-1}$	$0.12\ mg\ L^{-1}$	$0.25\ mg\ L^{-1}$	–	$0.01\ mg\ L^{-1}$	$0.001\ mg\ L^{-1}$
C. tritaeniorhynchus (larvae)	$0.3\ mg\ L^{-1}$	$0.12\ mg\ L^{-1}$	$0.25\ mg\ L^{-1}$	–	$0.01\ mg\ L^{-1}$	$0.001\ mg\ L^{-1}$
Ae. Albopictus (larvae)	–	$0.4\ mg\ L^{-1}$	$0.25\ mg\ L^{-1}$	–	$0.01\ mg\ L^{-1}$	$0.001\ mg\ L^{-1}$
Ae. aegypti (larvae)	$0.012\ mg\ L^{-1}$	$0.12\ mg\ L^{-1}$	–	–	$0.01\ mg\ L^{-1}$	$0.001\ mg\ L^{-1}$

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biological diagnosis, are being employed more and more extensively.[7]

3 ORGANOCHLORINE RESISTANCE

Organochlorines are the first type of chemical insecticide produced and applied in China since the 1950s and they have played an important role in agricultural development. DDT and BHC dominated the insecticide market (80.1% in 1970) until 1983, when their production was prohibited throughout the country owing to prevailing resistance in treated pests, contamination of the environment and human health concerns caused by their high persistence in the environment.[8]

Although mosquitoes have not been treated with DDT and BHC for many years, obvious resistance to DDT, but not to BHC, still exists in mosquito populations (Tables 2 and 3). For the *C. pipiens* complex, 50% of 20 investigated areas over seven provinces showed obvious resistance to DDT, 5% elementary resistance and 15% low resistance (Table 2). The resistance prevailed mainly in Hubei and Yunnan provinces. All of the seven areas investigated were sensitive to BHC (Table 2). Acetofenate is another organochlorine insecticide used commonly in China, but its application quantity and range are much less than those of DDT and BHC. Among 26 regions across five provinces, only low resistance to acetofenate was observed, and that in 58% of the regions (Table 2). For *A. sinensis*, resistance to DDT was found to be ubiquitous: 89% of 27 regions in five provinces exhibited obvious or elementary resistance (Table 3). The problem in Hubei and Yunnan province was quite striking. For *C. tritaeniorhynchus*, *A. minimus*,

Table 2. Resistance[a] to organochlorines and carbamates in the *Culex pipiens* complex

Province	City or county	Carbamate		Organochlorine			References	Year
		propoxur	BPMC	acetofenate	DDT	BHC		
Zh ejiang	Hangzhou	L	–	S	–	–	9	1999
	Jinhua	–	L	L	–	–	10	Not clear
	Jiaxing	–	L	S	S	–	10	Not clear
	Ningbo	S	S	S	–	–	11	1999
	Wenzhou	–	S	L	–	–	10	Not clear
	Linhai	–	S	S	–	–	12	Not clear
	Shaoxing	–	S	S	–	–	10	Not clear
	Quzhou	–	L	L	–	–	10	Not clear
	Huzhou	–	L	S	S	–	10	Not clear
	Zhuji	–	L	S	–	–	13	Not clear
	Shanghai	–	S	–	–	–	14	1998
Guangdong	Guangzhou	L	L	–	–	–	15	1997
	Foshan	S	L	–	–	–	15	1997
	Shenzheng	L	L	–	–	–	15	1997
	Shantou	L	L	–	–	–	15	1997
	Shaoguan	L	L	–	–	–	15	1997
	Maoming	L	L	–	–	–	15	1997
	Jiangmen	–	L	–	–	–	15	1997
Hubei	Shashi	–	–	–	R*	–	16	1991
	Hanchuan	–	–	–	R*	–	17	1995
	Jingzhou	–	–	–	R*	–	18	Not clear
Shandong	Gaomi	–	S	–	–	–	19	1998
	Jining	L	–	L	L	–	20	2001
	Zoucheng	L	–	L	–	–	20	2001
	Jiaxiang	L	–	S	–	–	20	2001
	Tengzhou	L	–	L	–	–	20	2001
	Tai'an	L	–	S	–	–	20	2001
	Dongying	–	S	–	–	S	21	Not clear
	Linyi	–	L	–	–	S	22	2000
Yunnan	Kunming	–	S	–	–	–	19	1998
	Guangnan	–	–	–	M*	–	23	1994
	Lushui	–	–	–	R*	–	23	1994
	Simao	–	–	–	R*	–	23	1994
	Zhenkang	–	–	–	R*	–	23	1994
	Lancang	–	–	–	R*	–	23	1994
	Shuangjiang	–	–	–	R*	–	23	1994
	Luxi	–	–	–	R*	–	23	1994
	Jinggu	–	–	–	R*	–	23	1994
Sichuan	Chengdu	S	S	–	–	S	24	1997

Table 2. Continued

Province	City or county	Carbamate		Organochlorine			References	Year
		propoxur	BPMC	acetofenate	DDT	BHC		
Hebei	Hengshui	S	–	–	–	S	25	1991
	Beijing	–	L	–	–	–	26	2001
	Tianjin	S	S,L	S,L	–	–	27	2002
Liaoning	Chaoyang	–	–	L	–	–	28	1996
	Panjin	–	–	S	–	–	28	1996
	Fuxin	–	–	S	–	–	28	1996
	Yingkou	–	–	L	–	–	28	1996
	Shenyang	–	–	–	S	–	29	2001
Guizhou	Guiyang	–	–	–	–	S	30	1998
	–	–	–	–	–	S	31	2002
Hainan	Haikou	–	–	–	L	–	32	1993
	Sanya	–	–	–	S	–	32	1993
Henan	Zhengzhou	–	L	–	L	–	33	2001,1992
	Luoyang	–	–	–	S	–	33	1991
	Jiaozuo	–	–	–	S	–	33	1991
	Shangqiu	–	L	–	–	–	26	2001
Jiangxi	Nanchang	S	L	L	–	S	34	1998
	Ganzhou	–	S	L	–	–	34	1998
	Jiujiang	–	S	L	–	–	34	1998
	Shangrao	–	S	L	–	–	34	1998
	Pingxiang	–	S	L	–	–	34	1998
	Xinyu	–	S	L	–	–	34	1998

[a] High resistance (H): resistance ratio (LC_{50} of field population/LC_{50} of susceptible strain) $>$ 20; moderate resistance (M): 10 $<$ resistance ratio $\leq$ 20; low resistance (L): 2 $\leq$ resistance ratio $\leq$ 10; susceptibility (S): resistance ratio $<$ 2; obvious resistance (R*): under the diagnosis dose, death $<$ 80%; elementary resistance (M*): under the diagnosis dose, 80% $\leq$ death $<$ 99%; susceptibility (S*): under the diagnosis dose, death $\geq$ 99%.

A. anthropophagus, *Ae. albopictus* and *Ae. aegypti*, resistance monitoring was carried out in very few areas, and the resistance level of each vector to DDT was variable (Table 3).

4 ORGANOPHOSPHATE RESISTANCE

OP insecticides have been used in China for more than 30 years. Over 20 OP species are produced currently, with an annual total production of over 1×10^8 kg.[8] Dichlorvos (DDVP) and trichlorfon are used extensively in controlling vectors,[5] while malathion, fenthion, fenitrothion, phoxim and parathion are used frequently in agriculture and gardens and thus inevitably exert selection pressure on mosquitoes. The use of parathion has now been banned in China.

For the *C. pipiens* complex, the monitoring of DDVP resistance has been the most extensive (Table 4). Among 69 regions of 14 provinces, 17% exhibited high resistance, 29% moderate or obvious resistance, 41% low resistance or elementary resistance and 13% susceptibility. Another OP insecticide that has been monitored broadly is malathion (Table 4). Among 26 regions of eight provinces, only 4% have shown high resistance, 19% obvious or moderate resistance, 42% low resistance and 35% susceptibility. Resistance monitoring of fenthion, trichlorfon, phoxim and parathion has been limited in the last 10 years (Table 4), but all the investigated areas displayed resistance to parathion to some extent. Broad monitoring of trichlorfon took place in the 1980s, and 31% of 32 investigated regions revealed moderate or high resistance, the most serious being in Shanghai and Guangzhou, where the resistance reached 75- and 43-fold respectively.[5] In summary, since the 1990s, the most serious and prevalent OP resistance problem has been to DDVP in the *C. pipiens* complex, and then to malathion, mainly in Guangdong, Hubei, Shandong, Henan, Jiangsu, Hebei and Jiangxi provinces.

For *A. sinensis*, only resistance monitoring to malathion and fenitrothion have been reported (Table 3). Obvious resistance to malathion was found in Hubei province. In Yunnan province, mosquitoes in most areas were sensitive to malathion and fenitrothion. For other vector mosquitoes, obvious resistance to DDVP was reported in *C. tritaeniorhynchus* in Hubei province, and obvious resistance to malathion was reported in *C. tritaeniorhynchus* in Sichuan province and in *Ae. aegypti* in Hainan province. *Anopheles minimus* has been investigated only in Yunnan province, where sensitivity to malathion and fenitrothion is common.

5 CARBAMATE RESISTANCE

The application of carbamates for controlling agricultural or sanitation pests began in around 1980 in China. There are about ten compounds, including propoxur, fenobucarb (BPMC), methomyl, carbofuran and carbaryl, and annual production is about 5×10^6 kg.[8] Resistance monitoring has been reported exclusively for propoxur and fenobucarb

Table 3. Insecticide resistance[a] of six vector mosquitoes

Mosquito species	Province	City or county	Organophosphate DDVP	Organophosphate Malathion	Organophosphate Fenitrothion	Pyrethroid Deltamethrin	Pyrethroid Permethrin	Organochlorine DDT	References	Year
A. sinensis	Hubei	Shashi	–	–	–	M*	M*	R*	16	1991
	–	Hanchuan	–	R*	–	S*	M*	R*	17	1995
	–	Jingshan	–	–	–	–	–	R*	35	1998
	–	Dahong	–	–	–	R*	–	R*	36	1998
	–	Jingzhou	–	R*, M*	–	M*	M*, S*	R*	18	Not clear
	Sichuan	Chengdu	–	M*	–	M*	–	R*	37	1995
	–	Neijiang	–	S*	–	M*	–	–	38	1992
	–	Chongqing	–	–	–	M*	M*	R*	38	1992
	–	Mingshan	–	–	–	M*	–	–	38	1992
	Zhejiang	Wenzhou	–	–	–	M	–	–	39	Not clear
	–	Jinhua	–	–	–	L	–	–	39	Not clear
	–	Ningbo	–	–	–	L	–	–	39	Not clear
	–	Hangzhou	–	–	–	L	–	–	39	Not clear
	–	Jiaxing	–	–	–	L	–	–	39	Not clear
	Fujian	Jianyang	–	–	–	M*	–	R*	40	1991
	–	Jian'ou	–	–	–	M*	–	–	40	1991
	–	Meilie	–	–	–	M*	–	S*	40	1991
	–	Ninghua	–	–	–	M*	–	R*	40	1991
	Jiangsu	Xuyi	–	–	–	M*	M*	–	41	2000
	–	Hongze	–	–	–	S*	M*	–	41	2000
	–	Sihong	–	–	–	S*	S*	–	41	2000
	Anhui	Ma'anshan	–	–	–	–	–	R*	42	1996
	Yunnan	Simao	–	S*	S*	R*	M*	R*	43	1992–1994
	–	Gengma	–	S*	–	S*	S*	S*	43	1992–1994
	–	Guangnan	–	S*	–	S*	S*	M*	43	1992–1994
	–	Jinping	–	M*	S*	S*	M*	R*	43	1992–1994
	–	Lancang	–	S*	S*	S*	M*	S*	43	1992–1994
	–	Lushui	–	S*	S*	S*	M*	R*	43	1992–1994
	–	Jinggu	–	S*	M*	M*	M*	M*	43	1992–1994
	–	Yuanmou	–	S*	S*	M*	M*	R*	43	1992–1994
	–	Yuanyang	–	–	–	–	–	R*	43	1992–1994
	–	Yuxi	–	S*	–	M*	M*	R*	43	1992–1994
	–	Suijiang	–	S*	S*	S*	M*	R*	43	1992–1994
	–	Kunming	–	S*	S*	M*	M*	R*	43	1992–1994
	–	Cangyuan	–	S*	S*	M*	M*	M*	43	1992–1994
	–	Jinghong	–	S*	S*	M*	S*	R*	43	1992–1994
	–	Wenshan	–	M*	S*	M*	M*	M*	43	1992–1994
	–	Hushui	–	S*	S*	S*	M*	R*	43	1992–1994
C. tritaeniorhynchus	Hubei	Shashi	R*	–	–	R*	R*	R*	16	1991
	Sichuan	Chengdu	–	R*	–	M*	–	M*	37	1995
A. minimus	Yunnan	Simao	–	S*	S*	S*	S*	S*	44	1997
	–	Yuanyang	–	S*	S*	M*	M*	S*	44	1997
	–	Daguan	–	S*	S*	S*	S*	S*	44	1997
	–	Luxi	–	S*	S*	R*	R*	S*	44	1997
	–	Yuanjiang	–	S*	–	M*	M*	M*	44	1997
A. anthropophagus	Sichuan	Ziyang	–	S*	–	–	–	–	38	1992
	–	Chengdu	–	–	–	S*	–	S*	37	1995
	Hubei	Dahong	–	–	–	M*	–	M*	36	1998
	–	Jingshan	–	–	–	–	–	M*	35	1998
	Fujian	Jianyang	–	–	–	S*	–	S*	40	1991
Ae. albopictus	Hainan	Haikou	S*	S*	–	R*	R*	H	32	1993
	–	Sanya	S*	S*	–	R*	M*	H	32	1993
Ae. aegypti	Hainan	Haikou	–	R*	–	R*	R*	R*	32	1993
	–	Sanya	–	R*	–	R*	M*	R*	32	1993

[a] H, M, L, S, R*, M* and S* as defined in Table 2.

Table 4. Resistance[a] to OPs in the *Culex pipiens* complex

Province	City or county	DDVP	Parathion	Trichlorfon	Malathion	Fenthion	Phoxim	References	Year
Zhejiang	Hangzhou	L	–	–	–	–	–	9	1999
	Taizhou	–	–	M	–	–	–	45	1995
	Zhoushan	–	–	L	–	–	–	45	1995
	Jinhua	L	–	–	–	–	–	10	Not clear
	Jiaxing	L	–	–	–	–	–	10	Not clear
	Ningbo	S	–	–	–	–	–	11	1999
	Wenzhou	L	–	–	–	–	–	10	Not clear
	Linhai	L	–	–	–	–	–	12	Not clear
	Shaoxing	L	–	–	–	–	–	10	Not clear
	Quzhou	L	–	–	–	–	–	10	Not clear
	Huzhou	L	–	–	–	–	–	10	Not clear
	Zhuji	L	–	–	–	–	–	13	Not clear
	Shanghai	H	L	–	–	–	–	14	1997, 1998
Guangdong	Guangzhou	H	H	–	H	S	–	15	1997
	Foshan	H	–	–	L	L	–	15	1997
	Shenzheng	–	–	–	M	–	–	15	1997
	Shantou	–	–	–	L	–	–	15	1997
	Shaoguan	–	–	–	L	–	–	15	1997
	Maoming	–	–	–	L	–	–	15	1997
	Jiangmen	–	–	–	L	–	–	15	1997
	Zhongshan	H	M	–	–	–	–	46	2001
Hubei	Shashi	R*	–	–	R*	–	–	16	1991, 1990
	Hanchuan	–	–	–	R*	–	–	17	1995
	Jingzhou	R*	–	–	R*	–	–	18	Not clear
Shandong	Gaomi	H	H	–	–	–	–	19	1998
	Jining	M, L	–	–	L	–	–	20	2001
	Zoucheng	M	–	–	–	–	–	20	2001
	Jiaxiang	L	–	–	–	–	–	20	2001
	Tengzhou	H	–	–	–	–	–	20	2001
	Tai'an	L	–	–	–	–	–	20	2001
	Pingyin	H	–	–	S	–	–	47	1994
	Dongying	M	–	–	–	–	–	21	Not clear
	Linyi	L	–	–	–	–	–	22	2000
Yunnan	Kunming	L	L	–	–	–	–	19	1998
	Guangnan	–	–	–	S*	–	–	23	1994
	Lushui	–	–	–	S*	–	–	23	1994
	Simao	–	–	–	S*	–	–	23	1994
	Zhenkang	–	–	–	S*	–	–	23	1994
	Shuangjiang	–	–	–	S*	–	–	23	1994
	Luxi	–	–	–	S*	–	–	23	1994
	Jinggu	–	–	–	S*	–	–	23	1994
Sichuan	Chengdu	L	–	–	S	L	–	24	1997
	Chongqing	S	–	–	–	–	–	48	2001
Jiangsu	Yangzhou	R*	–	–	–	–	–	49	1997
	Suzhou	R*	–	–	–	–	–	50	1995
	Nantong	R*	–	–	–	–	–	51	1998
Hebei	Shijiazhuang	L	–	–	–	–	–	52	1994
	Hengshui	S	–	S	–	–	–	25	1991
	Tangshan	S	–	–	–	–	–	53	1991
	Beijing	H	M	–	–	–	–	26	2001
	Tianjin	S, L, M	–	–	–	–	S, L, H	27	2002
	Cangzhou	R*	–	–	–	–	–	54	1992
	Beidaihe	M*	–	–	–	–	–	54	1992
	Hejian	R*	–	–	–	–	–	54	1992
	Baoding	M*	–	–	–	–	–	54	1992
	Xushui	M*	–	–	–	–	–	54	1992
	Chengde	M*	–	–	–	–	–	54	1992
	Longhua	M*	–	–	–	–	–	54	1992
	Handan	R*	–	–	–	–	–	54	1992
	Lingshou	R*	–	–	–	–	–	54	1992
	Zhangjiakou	S*	–	–	–	–	–	54	1992

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Table 4. Continued

Province	City or county	DDVP	Parathion	Trichlorfon	Malathion	Fenthion	Phoxim	References	Year
Liaoning	Chaoyang	L	–	–	–	–	–	28	1996
	Panjin	S	–	–	–	–	–	28	1996
	Fuxin	L	–	–	–	–	–	28	1991
	Yingkou	L	–	–	–	–	–	28	1992
	Shenyang	L	–	–	–	–	–	29	2001
Guizhou	Guiyang	S	–	S	–	–	–	30	1998
	–	M	–	S	–	–	–	31	2002
Hunan	Changsha	M	–	–	L	–	–	55	1993
	Zhuzhou	H	–	–	–	–	–	56	1998
Hainan	Haikou	L	–	–	L	–	–	32	1993
	Sanya	L	–	–	L	–	–	32	1993
Henan	Zhengzhou	H	L	–	M	–	–	26	2001, 1992
	Anyang	L	–	–	L	–	–	33	1992
	Luoyang	S	–	–	–	–	–	33	1991
	Jiaozuo	S	–	–	–	–	–	33	1991
	Shangqiu	H	L	–	–	–	–	26	2001
	Luohe	H	–	–	L	–	–	57	Not clear
Anhui	Ma'anshan	–	–	S	–	–	–	42	1996
Jiangxi	Nanchang	M	–	M	–	–	–	34	1998
	Ganzhou	M	–	–	–	–	–	34	1998
	Jiujiang	M	–	–	–	–	–	34	1998
	Shangrao	L	–	–	–	–	–	34	1998
	Pingxiang	M	–	–	–	–	–	34	1998
	Xinyu	M	–	–	–	–	–	34	1998

[a] H, M, L, S, R*, M* and S* as defined in Table 2.

in the *C. pipiens* complex. Only low resistance was observed in the eight provinces investigated, and in most regions the mosquitoes were found to be susceptible (Table 2). No data are available for other vector mosquitoes. Therefore, in China carbamate insecticides can still be applied to control vector mosquitoes efficiently.

6 PYRETHROID RESISTANCE

The exploitation of pyrethroids in China started at the beginning of the 1970s, and the application of this new type of insecticide has flourished in recent years. The area treated with pyrethroids occupies more than one-third of the total insecticide-treated area in China.[8] For the public health market, pyrethroids are used as indoor sprays or incense, or to impregnate bednets, curtains and screens. Many highly efficient, non-toxic pyrethroids are applied extensively in agriculture and public sanitation, such as cypermethrin, fenvalerate, deltamethrin, tetramethrin, permethrin, methothrin, allethrim, resmethrin and cyhalothrin. However, resistance has arisen quite quickly and is prevalent in many pest populations, including mosquitoes.

For the *C. pipiens* complex, resistance monitoring to cypermethrin, deltamethrin, tetramethrin, permethrin and allethrim is recorded (Table 5). Among 21 regions from eight provinces, 43% exhibited high resistance to cypermethrin, 43% moderate or low resistance and 14% susceptibility. Of 66 regions from 12 provinces, 17% were highly resistant to deltamethrin, 35% were moderately or obviously resistant, 39% were low or elementarily resistant and only 9% were still sensitive to this insecticide. Among 51 regions from 12 provinces, 10% showed high resistance to permethrin, 24% moderate or obvious resistance, 47% low or elementary resistance and 20% sensitivity. The investigations on tetramethrin and allethrim were not as broad, and most regions showed low resistance or sensitivity to them (Table 5). Overall, more attention should be paid to the problem of resistance of the *C. pipiens* complex to pyrethroids in the provinces of Guangdong, Hubei, Shandong and Jiangxi.

For other vector mosquitoes, deltamethrin and permethrin are the major pyrethroid insecticides whose resistance situations are monitored (Table 3). *Anopheles sinensis*, *A. minimus* and *A. anthropophagus* show elementary resistance or sensitivity to these two insecticides in most of the regions investigated. *Aedes albopictus* and *Ae. aegypti* in Hainan province show obvious resistance to them.

7 CONCLUDING REMARKS

Insecticides play important roles in agricultural production and public health, especially in countries like China with a huge human population. Large quantities of various kinds of insecticide are applied in fields or indoors, directly or indirectly bringing selection pressure on vector mosquitoes. Consequently, resistance appears in vector mosquitoes and makes their control increasingly difficult. The seven major species of vector mosquito in China have evolved an ability to resist

Table 5. Resistance[a] to pyrethroids in the *Culex pipiens* complex

Province	City or county	Cypermethrin	Deltamethrin	Tetramethrin	Permethrin	Allethrim	References	Year
Zhejiang	Hangzhou	–	L	–	L	–	9	1999
	Jinhua	–	L	–	M	–	10	Not clear
	Jiaxing	L	M	–	L	L	10	Not clear
	Ningbo	L	S	L	L	L	11	1999
	Wenzhou	–	L	–	L	–	10	Not clear
	Linhai	–	L	–	S	–	12	Not clear
	Shaoxing	–	L	–	L	–	10	Not clear
	Quzhou	–	L	–	L	–	10	Not clear
	Huzhou	L	L	–	L	L	10	Not clear
	Zhuji	–	L	–	L	–	13	Not clear
	Shanghai	M, L	M, L, S	–	–	–	58	1997
Guangdong	Guangzhou	H	H	–	H	L	15	1997
	Foshan	–	L	–	H	S	15	1997
	Shenzheng	M	H	–	H	S	15	1997
	Shantou	H	M	–	M	S	15	1997
	Shaoguan	M	M	–	M	S	15	1997
	Maoming	L	M	–	L	S	15	1997
	Jiangmen	–	M	–	H	L	15	1997
Hubei	Shashi	–	R*	R*	R*	–	16	1991,1990
	Hanchuan	–	M*	–	M*	–	17	1995
	Jingzhou	–	R*	–	R*, S*	–	18	Not clear
Shandong	Jining	H	M	–	L	–	20	2001
	Zoucheng	H	M	–	–	–	20	2001
	Jiaxiang	H	L	–	–	–	20	2001
	Tengzhou	H	M	–	–	–	20	2001
	Tai'an	H	M	–	–	–	20	2001
	Pingyin	–	S	–	S	–	47	1994
	Dongying	–	–	L	L	–	21	Not clear
	Linyi	L	M	M	H	–	22	2000
Sichuan	Chengdu	S	H	L	M	L	24	1997
	Chongqing	S	S	–	–	–	48	2001
Jiangsu	Yangzhou	–	R*	–	R*	–	49	1997
	Suzhou	–	M*	–	R*	–	50	1995
	Nantong	–	M*	–	M*	–	51	1998
Hebei	Shijiazhuang	–	L	–	L	–	52	1994
	Hengshui	S	S	S	S	–	25	1991
	Tangshan	–	H	–	S	–	53	1991
	Tianjin	–	S, L	–	S, L	–	27	2002
	Cangzhou	–	R*	–	R*	–	54	1992
	Beidaihe	–	R*	–	R*	–	54	1992
	Hejian	–	R*	–	M*	–	54	1992
	Baoding	–	M*	–	M*	–	54	1992
	Xushui	–	M*	–	R*	–	54	1992
	Chengde	–	M*	–	M*	–	54	1992
	Longhua	–	M*	–	S*	–	54	1992
	Handan	–	M*	–	M*	–	54	1992
	Lingshou	–	M*	–	S*	–	54	1992
	Zhangjiakou	–	M*	–	M*	–	54	1992
Liaoning	Chaoyang	–	S	–	–	–	28	1996
	Panjin	–	S	–	–	–	28	1996
	Fuxin	–	L	–	–	–	28	1996
	Yingkou	–	L	–	–	–	28	1996
	Shenyang	L	L	–	S	–	29	2001
Guizhou	Guiyang	–	–	–	S	–	30	1998
	–	–	–	–	M	–	31	2002
Hunan	Changsha	–	M	–	S	–	55	1993
	Zhuzhou	H	M	H	–	–	56	1998
Hainan	Haikou	–	H	–	L	–	32	1993
	Sanya	–	H	–	S	–	32	1993

Table 5. Continued

Province	City or county	Cypermethrin	Deltamethrin	Tetramethrin	Permethrin	Allethrim	References	Year
Henan	Anyang	–	M	–	L	–	33	1992
	Luoyang	–	H	–	L	–	33	1991
	Jiaozuo	–	L	–	L	–	33	1991
	Luohe	H	H	–	–	–	57	Not clear
Jiangxi	Nanchang	–	M	L	–	L	34	1998
	Ganzhou	–	H	–	–	–	34	1998
	Jiujiang	–	M	–	–	–	34	1998
	Shangrao	–	H	–	–	–	34	1998
	Pingxiang	–	M	–	–	–	34	1998
	Xinyu	–	H	–	–	–	34	1998

[a] H, M, L, S, R*, M* and S* as defined in Table 2.

to some extent all the types of insecticide except carbamates. The severity varies among mosquito species, insecticide type and region. To delay the upgrade and spread of resistance, scientific and reasonable measures should be taken, such as the use of mixtures or mosaics of different insecticides and regular monitoring of resistance levels. On the other hand, exploration on the resistance mechanisms will not only enhance development of new classes of insecticides but will also make it possible to attack existing insecticide resistance and to boost the lifespan of currently available insecticides, thus fundamentally improving the control of vector-borne diseases.

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