BIOLOGICAL CONTROL OF INSECT PESTS: SOUTHEAST ASIAN PROSPECTS

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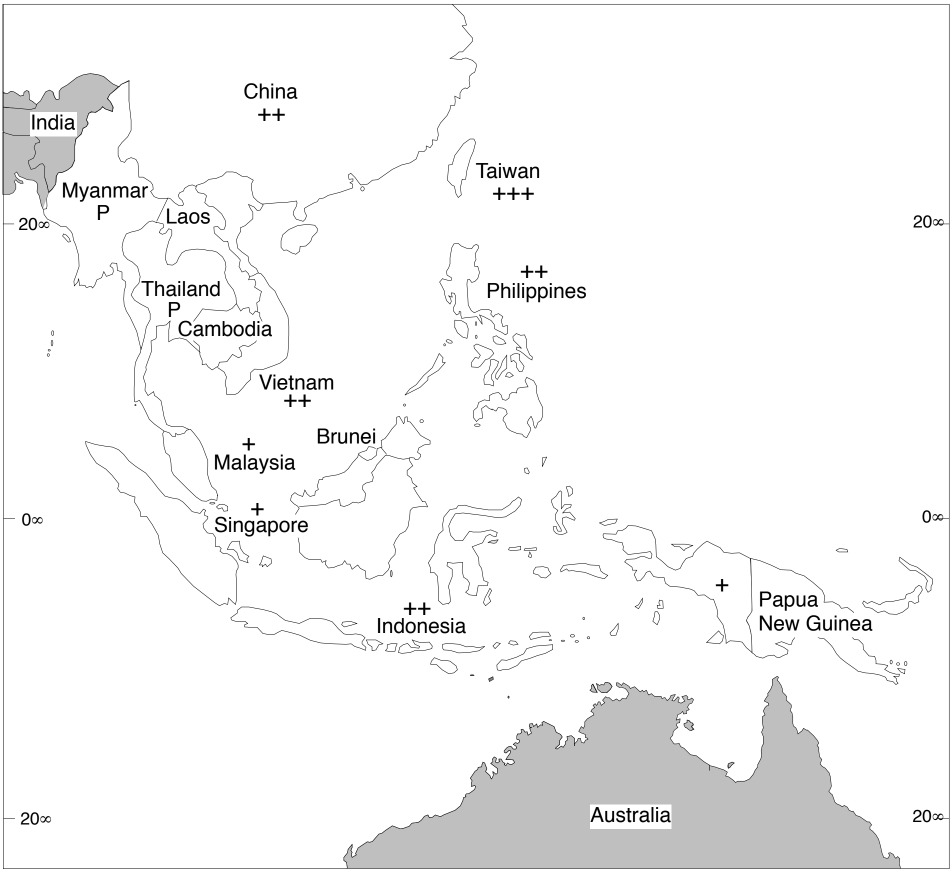
4.7 *Diaphorina citri*



The citrus psyllid *Diaphorina citri* is native to the Indo-Malaysian region, but has spread outside it to Réunion, Mauritius, Saudi Arabia, Honduras, and Brazil. The sap it removes from new flushes of citrus growth is of minor consequence, but it is the vector of a devastating bacterial disease, citrus greening.

Its major controlling factors are high rainfall (washing off eggs and young nymphs) and two parasitoids, *Tamarixia radiata* and *Diaphorencyrtus aligarhensis*. Where these parasitoids are native they are very heavily attacked by hyperparasitoids which diminish their effectiveness. Freed of these hyperparasitoids *T. radiata* has been established in 3 countries where it was not present: Réunion, Madagascar and Taiwan, resulting in excellent biological control. Although *T. radiata* appears to be widespread in Southeast Asia, observations might well disclose regions where it is not present and could be introduced with advantage. The prospects for successful biological control of *D. citri* are good when it invades regions where hyperparasitoids of *T. radiata* are absent or deficient.

Diaphorina citri Kuwayama

Hemiptera, Psyllidae

citrus psyllid, Asian citrus psyllid

Rating

	Southeast Asia		China	Southern and Western Pacific
8	++	Viet, Indo, Phil	3+++	absent
	+	Msia, Sing		
	P	Myan, Thai		

These Southeast Asian ratings arose from an earlier survey of country opinions (Waterhouse 1993b) and may not reflect current assessments.

Origin

The Indo-Malaysian region. *D. citri* was described from Punjab, India (Waterston 1922). There is evidence of recent spread into the southeastern and eastern portions of Southeast Asia.

Distribution

D. citri is widespread from Afganistan eastwards through Pakistan, India, Nepal and Bhutan to Southeast Asia, southern China (up to about 30°N, Xie et al. 1988), Taiwan (Catling 1970; Tsai et al. 1984; Aubert 1990) and the Ryuku Is (Japan) (Miyakawa and Tsuno 1989). It has recently become established in Ende (Flores) and Timor and in Irian Jaya (Aubert 1989b, 1990). *D. citri* was collected in June 1993 in the Jayapura area of Irian Jaya and citrus there showed symptoms of greening (Northern Australia Quarantine Strategy 1993). It has been introduced to Réunion, Mauritius, Comoro Is (Hollis 1987), Saudi Arabia (Wooler et al. 1974), Yemen (Bové 1986), Brazil (Silva et al. 1968; Bergmann et al. 1994) and Honduras (Burckhardt and Martinez 1989). In 1990 there were still limited areas free of *D. citri* in east Mindoro (Philippines) and Palau and Tambun (Malaysia). It is not yet recorded from Papua New Guinea and does not occur in Australia, the Oceanic Pacific or North America.

In Réunion it has not colonised citrus plantings above 800 m, where the lowest temperature is 7°C, whereas in Malaysia the height limit is 1200 m with a minimum temperature of 14°C.

Biology

D. citri survives a wide range of temperature extremes from 45°C in Saudi Arabia to –7° to –8°C in China, thereby tolerating cold that will kill citrus (Xie et al. 1989a). Far more than temperature, high humidity and rainfall are important limiting factors, rain by washing off eggs and early instar nymphs and humidity by favouring fungal attack. These two factors are mainly responsible for the low *D. citri* populations on the windward (rainy) side of Mindoro (Philippines) and Réunion (Aubert 1989a).

There have been several studies on the life cycle of *D. citri*, which conform generally with the results in Table 4.7.1, leading to up to 11 generations a year in Fujian Province, China (Xu et al. 1988b, 1994). *D. citri* has a short life cycle and high fecundity and is commonest in hot coastal areas. Mating commences soon after the insects become adult and, after a pre-oviposition period of about 12 days, eggs are laid singly inside half-folded leaves of buds, in leaf axils and other places on the young tender shoots. Average adult lifespan is 30 to 40 days, although overwintering adults had a lifespan of 260 days (Xu et al. 1994).

Table 4.7.1 Bionomics of *D. citri* (average in days) in Fujian Province, China (Xu et al. 1988b)

	Adult life-span		Eggs per female	Incubation	Nymphal development	Egg–adult
	Max	Min				
Spring	96	28.1	17.7	10	31.8	42
Summer	46	19.7	43.8	2	10.3	13
Autumn	59	31.6	22.6	4	16.8	21
Winter	131–165					

The abundance of both eggs and nymphs is correlated with the availability of new growth flushes and breeding is largely suspended when trees become dormant. On its favoured host plant *Murraya paniculata* in Fujian, populations may average 51 adults per young shoot and a 4-year-old plant produces 900–1000 shoots. On mandarin (*Citrus reticulata*) the average colony size is 20 per shoot, with 600 to 650 shoots, and peak abundance occurs about 6 weeks later than on *M. paniculata* (Aubert 1990). *D. citri* nymphs develop well under cool, humid spring conditions, but are seriously affected by fungal infections under hot, humid conditions. On *M. paniculata*, adult numbers were highest on leaf midveins (43%), followed by petioles (30.7%), leaf blades (23.7%) and stems (2.6%) (Tsai et al. 1984).

D. citri nymphs normally lead a sedentary existence clustered in groups, but will move away when disturbed. Adults are 2.5 mm long and jump when disturbed, whereupon they may fly up to 5 m before settling again. Seasonal migratory flights occur when adults fly up to about 7 m above ground level, entering mild winds which may carry them up to 4 km distant (Aubert 1990). Flying adults are attracted to yellow traps, which have been used for sampling (Aubert and Xie 1990). Adult *D. citri* have yellowish-brown bodies, greyish-brown legs and transparent wings. They have white spots or are light brown with a broad, beige, longitudinal, central band.

Host plants

D. citri feeds and breeds on the entire group of horticultural *Citrus*, with additional hosts in eight different genera belonging to the Aurantoidea (Aubert 1990). *D. citri* thus has a wider host range than the greening organism it transmits to citrus (see Damage). An indication of the relative suitability of its various host plants is shown in Table 4.7.2, although there may be local modifications of the groupings. This is probably due to different *D. citri* biotypes. For example, unlike Réunion populations, Malaysian populations breed well on *Bergera koenigii* and, in the Philippines, adults are more attracted by *Clausena anisumolens* than by *Murraya paniculata* (Aubert 1990). Overall, jasmin orange, *Murraya paniculata,* is the preferred host and this plant is widely grown in Southern and Southeast Asia as an ornamental shrub and hedge plant.

Damage

Although sap removal by large populations of *D. citri* can cause young foliage on flushes of growth to wilt, by far the most damaging effect of feeding is due to the transmission of a gram-negative bacterium which is the cause of citrus greening, known as huanglungbin in China (Xu et al. 1988a). Citrus greening is known to affect 3 genera of the subtribe Citrinae, namely *Citrus*, *Poncirus* and *Fortunella* (Aubert 1990). It has also been experimentally transferred from *Citrus* to Madagascar periwinkle (*Catharanthus roseus* (Ke 1987). Once infected with the bacterium, *D. citri* remains infective for its lifetime, but does not pass on the infection transovarially. Amongst citrus, pummelo and lemon are less affected by greening than most other species. *D. citri* is the only known vector of citrus greening in Asia, although several other psyllids attacking citrus have been described: *D. auberti* (Comoro Is: Hollis 1987), *Psylla citricola*, *P. citrisuga* and *Trioza citroimpura* (China: Yang and Li 1984) and *Psylla murrayii* (Malaysia: Osman and Lim 1990).

Table 4.7.2 *Diaphorina citri* host plants (after Aubert 1990)

		Leaf sucking	Egg laying	Nymphal development
Preferred host plant	*Murraya paniculata* (jasmin orange)	+++	+++	+++
Good host plants	*Citrus aurantifolia* (lime) *Bergera (Murraya) koenigii* (curry bush)	+++	+++	+++
Common host plants	*Citrus limon* (lemon) *Citrus sinensis* (sweet orange) *Citrus medica* (citron) *Citrus reticulata* (mandarin) *Microcitrus australisiaca** *Citrus maxima* var. *racemosa* (pummelo) *Citrus hystrix* (*Mauritius papeda*) *Citrus madurensis* *Clausena excavata* *Clausena lansium*	++	++	++
Occasional host plants	*Citrus maxima* (pummelo)	+	+	+
	*Triphasia trifoliata**	+	+	+
	Fortunella sp.* (kumquat)	+	+	+
	*Poncirus trifoliata**	+	+	–
	Clausena anisumolens (anise)	+	+	+
	*Merrillia caloxylon**	+	–	–
	*Toddalia asiatica**	+	–	–

Table 4.7.2 (cont'd) *Diaphorina citri* host plants (after Aubert 1990)

		Leaf sucking	Egg laying	Nymphal development
Occasional host plants	*Vepris lanceolata**	+	–	–
	*Swinglea glutinesa**	+	unknown	unknown
	Atalantia sp.	+	unknown	unknown
	*Clausena indica**	+	unknown	unknown
	*Murraya exotica**	+	unknown	unknown

Citrus species hosts are, according to the classification of Jones (1990):
+++ very common;
++ usual
+ occasional;
– complete life cycle not observed
*observations on caged insects

In Africa, Réunion, Madagascar and Saudi Arabia another psyllid *Trioza erytreae* transmits a slightly different citrus greening organism (see later under Réunion).

Citrus greening is believed to have originated in northeastern Guangdong Province (Lin and Lin 1990). Amongst other symptoms, the leaves of new green shoots first turn yellow at their base, then often become mottled yellow and drop. The branches remain small, upright and stiff. Diseased trees flower abundantly in the off-season and flowers drop readily or result in small, irregular fruit whose base turns red before the remainder changes from green (Ke 1987). Citrus greening is widespread throughout South and Southeast Asia, where it is almost always the most serious disease of citrus. It is spread to new areas by infected nursery plants or infected budwood and within orchards by *D. citri* (Capoor et al. 1967; Whittle 1992). However, *D. citri* has been intercepted by quarantine in France on citrus imported from Honduras (Burckhardt and Martinez 1989). The tonnage of citrus produced worldwide is second as a fruit crop only to that of grapes (Aubert 1987b). An extremely serious citrus disease which already affects nearly 50 countries in Asia and Africa must, therefore, be regarded as of major importance. It is reported that a total of over a million trees are destroyed each year in China, Thailand, Malaysia, Indonesia and Philippines alone (Aubert 1987a). In Indonesia citrus greening has caused the loss of many millions of trees. Small farmers are frequently reluctant to remove declining trees before they almost cease bearing. This tends to increase *D. citri* populations, which breed on young flush since a symptom of greening is unseasonal flushing (Whittle 1992). The recent history of production in northern Vietnam, where citrus is grown mainly in larger orchards or state farms, is typically cyclical, with the gradual destruction of trees by greening and then wholesale removal and replanting. A new cycle of planting commenced in the late 1980s, but greening is already to be seen in many young orchards, although populations of *D. citri* are still low (Whittle 1992). Only by keeping populations at very low levels by biological control and/or insecticides will the rate of spread of greening be diminished. Insecticides are said to be highly cost effective if used only during a restricted flushing period, but if needed frequently they are very costly and environmentally undesirable. Recent developments with carefully specified, highly refined petroleum oils has given high levels of control of *D. citri* (A. Beattie pers. comm. 1995), with presumably little direct effect on its parasitoids. Whittle (1992) reported that he was unable to find *D. citri* in the vicinity of Ho Chi Minh City (southern Vietnam), a very unusual situation for an area with a fairly long history of citrus cultivation.

The Asian citrus greening bacterium can withstand high temperatures and occurs in China, Southeast Asia, India and Saudi Arabia. On the other hand, Southern African greening, which is transmitted by the psyllid *Trioza erytreae*, is heat-sensitive and symptoms do not develop in climates where temperatures above 30°C are recorded for several hours a day. In addition to Southern Africa, this greening occurs also in North Yemen (Garnier et al. 1988).

Natural enemies

Identified natural enemies are listed in Table 4.7.3. There are also reports of a number of unidentified predators (coccinellids, chrysopids, mantids, spiders). It is noteworthy that only 2 primary parasitoids—both attacking *D. citri* nymphs—have so far been recorded, the widespread endoparasitic encyrtid *Diaphorencyrtus aligarhensis* and the more restricted ectoparasitic eulophid *Tamarixia radiata*, which has been introduced to several countries for biological control. Both feed on the haemolymph of some hosts, resulting in their death, as well as using other hosts for oviposition.

Where they occur naturally, both *D. aligarhensis* and *T. radiata* are heavily attacked by a wide range of hyperparasitoids (Table 4.7.4). Of these, *Tetrastichus* sp. is the most important for *T. radiata*, causing an average of 21.8% parasitisation in 1988 (rising to a maximum of 87.9%) and 28.7% in 1989 in Fujian Province, China. *Chartocerus walkeri* (9.3% in 1988 and 13.2% in 1989) is the most important for *D. aligarhensis* (Table 4.7.5).

A valuable illustrated guide to the hyperparasitoids associated with *D. citri* is provided by Qing and Aubert (1990).

Table 4.7.3 Natural enemies of *Diaphorina citri* (* indicates introduced to this country)

Species	Region	Reference
HYMENOPTERA		
ENCYRTIDAE		
Diaphorencyrtus aligarhensis	India	Shafee et al. 1975; Hayat 1981
(= *Aphidencyrtus diaphorinae*	Vietnam	Myartseva & Tryapitzyn 1978;
= *Diaphorencyrtus diaphorinae*		van Lam 1996
= *Psyllaephagus diaphorinae*		Prinsloo 1985
= *Aphidencyrtus aligarhensis*)	Taiwan	Lin & Tao 1979
	Comores Is	Aubert 1984b
	Réunion	Aubert & Quilici 1984, Quilici 1989
	Philippines	Prinsloo 1985; Gavarra & Mercado 1989; Gavarra et al. 1990
	China	Tang 1989
	Indonesia	Nurhadi 1989; Nurhadi & Crih 1987
	Malaysia	Lim et al. 1990
EULOPHIDAE		
Tamarixia radiata	India	Waterston 1922; Husain & Nath 1924; Quilici 1989,
(= *Tetrastichus radiatus*)	Réunion*	Etienne and Aubert 1980
	Saudi Arabia	Aubert 1984a
	Mauritius*	Aubert 1984c
	Nepal	Lama et al. 1988; Otake 1990
	Taiwan*	Chiu et al. 1988
	China	Liu 1989; Tang 1989; Qing & Aubert 1990
	Indonesia	Nurhadi & Crih 1987; Nurhadi 1989
	Malaysia	Lim et al. 1990
	Thailand	Qing & Aubert 1990
	Vietnam	Myartseva & Trijapitzyin 1978; van Lam 1996

Table 4.7.3 (cont'd) Natural enemies of *Diaphorina citri* (* indicates introduced to this country)

Species	Region	Reference
COLEOPTERA		
COCCINELLIDAE		
Cheilomenes sexmaculata	China	Xia et al. 1987
NEUROPTERA		
CHRYSOPIDAE		
Chrysopa boninensis	China	Liu 1989
ARACHNIDA		
SALTICIDAE		
Marpissa tigrina	India	Sanda 1991
FUNGI		
Beauveria bassiana	China	Chen et al. 1990
Cephalosporium (= *Verticillium*) *lecanii*	China	Xie et al. 1988
Fusarium lateritium	China	Xie et al. 1988
Paecilomyces sp.	China	Xie et al. 1988

Table 4.7.4 Hyperparasitoids of *Diaphorina citri* (mostly after Tang 1989)

Hyperparasitoid	Attacks	Region	Reference
EULOPHIDAE			
Tetrastichus sp.	*T.r.* & *D.a.*	China	Tang 1989
	D.a.	Taiwan	Hayat & Lin 1988; Chien et al. 1989
		Philippines	Balthazar 1966, unpublished
ENCYRTIDAE			
Syrphophagus taiwanus	*T.r.* & *D.a.*	Taiwan	Hayat & Lin 1988; Chien et al. 1989
	T.r. & *D.a.*	China	Tang 1989
Ageniaspis sp.	*D.a.*	Taiwan	Hayat & Lin 1988; Chien et al. 1989
Cheiloneurus sp.	*D.a.*	Taiwan	Hayat & Lin 1988; Chien et al. 1989,
	?	Philippines	Baltazar 1966, unpublished
?*Psyllaephagus* sp.	*T.r.* & *D.a.*	China	Tang 1989
		Philippines	Balthazar 1966, unpublished
			Tang 1989
Several unidentified	*D.a.*	China	Tang 1989
SIGNIPHORIDAE			
Chartocerus walkeri	*T.r.* & *D.a.*	Taiwan	Hayat & Lin 1988; Chien et al. 1989
	T.r. & *D.a.*	China	Tang 1989
Signiphora sp.	*D.a.*		Gavarra et al. 1990
PTEROMALIDAE			
Pachyneuron concolor	*T.r.* & *D.a.*	Taiwan	Hayat & Lin 1988; Chien et al. 1989
APHELINIDAE			
Coccophagus ceroplastae	*D.a.*	Taiwan	Hayat & Lin 1988; Chien et al. 1989
Coccophagus sp.	*D.a.*	Taiwan	Hayat & Lin 1988; Chien et al. 1989

Table 4.7.4 (cont'd) Hyperparasitoids of *Diaphorina citri* (mostly after Tang 1989)

Hyperparasitoid	Attacks	Region	Reference
APHELINIDAE (cont'd)			
Marietta leopardina	*T.r.* & *D.a.*	Taiwan	Hayat & Lin 1988; Chien et al. 1989
(= *Marietta javensis*)	*D.a.*	Philippines	Balthazar 1966, unpublished
Encarsia spp.	*T.r.* & *D.a.*	Taiwan	Hayat & Lin 1988; Chien et al. 1989
		China	Tang 1989
Unidentified sp.	*T.r.* & *D.a.*	Taiwan	Chien et al. 1989

T.r. = *Tamarixia radiata* *D.a.* = *Diaphorencyrtus aligarhensis*

Table 4.7.5 Hyperparsitoids of *Tamarixia radiata* and *Diaphorencyrtus aligarhensis* in Fujian and Taiwan (after Qing 1990)

	Percentage of hyperparasitisation					
		T. radiata			***D. aligarhensis***	
Hyperparasitoid	**Fujian**	**Fujian**	**Taiwan**	**Fujian**	**Fujian**	**Taiwan**
EULOPHIDAE						
Tetrastichus sp.	21.82	28.65	0.01	2.90	3.68	
PTEROMALIDAE						
Pachyneuron concolor			0.45			18.50
SIGNIPHORIDAE						
Chartocerus walkeri	0.08	1.09	0.03	9.26	13.16	13.50
ENCYRTIDAE						
Syrphophagus taiwanus			0.05	1.09	4.21	6.80
?*Psyllaephagus* sp.	0.04	0.10		10.35	6.58	
Cheiloneurus sp.						0.01
Ageniaspis sp.						
unidentified sp.A				3.45	0.26	
Sp.B				0.91		
Sp.C				0.18		
Sp.D				0.18		
APHELINIDAE						
Encarsia sp. near *transvena* (= *E. shafeei)*			0.11			0.80
Encarsia sp. A	0.08	0.10		0.91	1.05	
Encarsia sp. B	0.22	0.20		0.91		

Table 4.7.5 (cont'd) Hyperparsitoids of *Tamarixia radiata* and *Diaphorencyrtus aligarhensis* in Fujian and Taiwan (after Qing 1990)

	Percentage of hyperparasitisation					
	T. radiata			***D. aligarhensis***		
Hyperparasitoid	**Fujian**	**Fujian**	**Taiwan**	**Fujian**	**Fujian**	**Taiwan**
APHELINIDAE (cont'd)						
Marietta leopardina			0.25			2.50
Coccophagus ceroplastae						0.01
Coccophagus sp.						0.10
Unidentified sp.			0.05			0.01
Totals	22.24	30.14	0.90	30.14	28.94	39.72

It is noteworthy that *T. radiata*, which has fairly recently (1984–1988) been introduced into Taiwan, was hyperparasitised to the extent only of 0.95% in 1989, whereas 42.2% of the native *D. aligarhensis* was attacked (Qing 1990).

The levels of hyperparasitisation of both primary parasitoids seriously affects their capacity to develop high populations and hence to produce maximum reduction of host populations. Nevertheless, each primary parasitoid killed is also a *D. citri* killed, so the overall mortality of *D. citri* is the sum of the mortalities produced by both primary parasitoids and their hyperparasitoids. It is abundantly clear that all hyperparasitoids must be rigorously excluded when transferring primary parasitoids from one region to another.

Attempts at biological control

The parasitoid *Tamarixia radiata*, obtained originally from India, has been used in successful biological control projects in Réunion, Mauritius and Taiwan and in an attempt in the Philippines (Table 4.7.6). These projects and comments on the situation in several other countries follow.

Table 4.7.6 Introductions for the biological control of *Diaphorina citri*

Species	From	To	Year	Result	Reference
EULOPHIDAE					
Tamarixia radiata	India	Réunion	1978	+	Aubert & Quilici 1984; Quilici 1989
	Réunion	Mauritius	after 1978	+	Quilici 1989
	Réunion	Taiwan	1983–86	+	Chiu et al. 1988; Chien et al. 1988
	Réunion	Philippines	1989	+	Gavarra et al. 1990
				?	Mercado et al. 1991

CHINA

In Guangdong, predators (lacewings, ladybird beetles, thrips, spiders) caused about 80% mortality of *D. citri*. Duration of daylight (short days reducing oviposition), quality of the flushes, and pesticide usage were other important factors influencing *D. citri* populations (Chen 1988). It appears that some Chinese farmers may spray citrus up to 50 times a year.

In Fujian there are 8 generations a year of *D. citri* on jasmin orange, *Murraya paniculata* and populations reach their peak in summer and early autumn during hot, dry weather when fresh shoots appear regularly. Populations are lowest in cold, wet weather with average temperatures of

9.1° to 12.2°C. Rainfall affects populations since eggs are laid on very young twigs and are easily washed off. A *Tamarixia* sp. was recorded in September 1987 and caused 83.3% parasitisation of nymphs in late autumn. In spring 1988 its population was low, but *D. citri* mainly overwinters as the adult and *Tamarixia* only attacks nymphs. Predators included coccinellids (especially *Cheilomenes sexmaculata* and *Harmonia axyridis*), lacewings, spiders and praying mantids (Xia et al. 1987; Ke 1991).

In Guangdong a maximum of 75% mortality of *D. citri* was recorded as being due to the hyperparasitoid *Tetrastichus* sp. (Liu 1989).

Beauveria bassiana (Chen et al. 1990a), *Cephalosporium* (*Verticillium*) *lecanii* and two other fungi (*Fusarium lateritium* and *Paecilomyces* sp.) were found attacking *D. citri*. Suspensions of *C. lecanii* sprayed on to *D. citri* displayed a very high pathogenicity (Xie et al. 1988, 1989b).

INDONESIA

Citrus greening is also known as citrus vein phloem degeneration. In East Java, both *T. radiata* (the commoner) and *D. aligarhensis* (the more widespread) were found in 1987 attacking *D. citri* on *Murraya paniculata* (Nurhadi and Crih 1987). *D. citri* is known to occur in Irian Jaya and may have been introduced in recent times, but it is not known if it is parasitised there.

MALAYSIA

Both *Tamarixia radiata* and *Diaphorencyrtus aligarhensis* are present with parasitisation rates ranging up to 28% in 4th and 5th instar nymphs (Osman and Quilici 1991) or up to 36% parasitisation (Lim et al. 1990). *T. radiata* is also present in Sarawak (S. Leong, pers. comm. 1995).

NEPAL AND BHUTAN

Both *T. radiata* and *D. aligarhensis* are present in some parts of both counties and may cause parasitisation of *D. citri* in excess of 90% (Lama and Amtya 1991; Lama et al. 1987).

PHILIPPINES

Citrus greening, also known as citrus leaf mottle, was already causing serious damage in the early 1960s. However, as late as 1988, the windward side of Mindoro island with an average rainfall of 3000 mm was virtually free of *D. citri* and citrus greening, presumably due to the adverse effects of high rainfall (Aubert 1989a). *D. aligarhensis* was reared from *D. citri* (25.7% parasitisation) and also 4 hyperparasitoids (*Marietta* sp. and 3 unidentified species), resulting in an overall mortality of *D. citri* of 48.3%. A *Beauveria* sp. attacked many psyllids and in turn was parasitised by another ascomycete, probably a *Melanospora* sp. (Gavarra and Mercado 1989). Later (Mercado et al. 1991), up to 62.2% parasitisation by *D. aligarhensis* was reported in Mindoro. In another study, Gavarra et al. (1990) recorded that, in addition to the primary parasitoid *D. aligarhensis* (17.6 to 36.1% parasitisation), 5 hyperparasitoids were reared from *D. citri*: *Marietta leopardina* (= *M. javensis*), *Tetrastichus* sp., *Psyllaephagus* sp., *Chiloneurus* sp. and *Signiphora* sp.

Because it was apparently absent from the Philippines (Baltazar 1966), *Tamarixia radiata* was introduced from Réunion in 1988, but attempts to rear it failed. A second consignment late that year was soon followed by the discovery of it nearby in the field in April 1989, with recoveries continuing in 1990 (Gavarra et al. 1990). However, Mercado et al. (1991) expressed some doubts that it had become established. It is thus not clear whether *T. radiata* ever occurred naturally in the Philippines.

RÉUNION

The rainy, windward, east side of Réunion has much lower *D. citri* populations and citrus trees there are much less exposed to transmission of greening (Aubert 1989a). Quilici (1989) has provided a valuable overview of the biological control of citrus psyllids in Réunion. In the early 1970s, Réunion and Mauritius were the only places known where *Diaphorina citri* and *Trioza erytreae*, the two psyllid vectors of citrus greening disease, occurred (Aubert 1987c). (Both are now known also from Saudi Arabia and Yemen: Bové 1986). Both psyllids were abundant in Réunion and Mauritius and citrus greening was seriously affecting citrus production in both islands. The Asian citrus psyllid *D. citri* was most abundant below 500 m in the hotter and drier leeward side of Réunion, where the average rainfall is below 1000 m. On the other hand, the drought-sensitive African psyllid *T. erytreae* was particularly abundant in the cooler, moister regions above 600 m. The only nymphal parasitoid of both species was the relatively ineffective *D. aligarhensis*. Several predators exerted little control.

Tamarixia dryi was introduced in 1974 from South Africa and, after elimination of hyperparasitoids, was mass produced and released in neglected, unsprayed citrus orchards colonised by *D. citri*. Populations of *Trioza erytreae* diminished progressively from 1979 to 1982, since when *T. erytreae* has not been recorded, although *Tamarixia dryi* is still abundant on another psyllid, *Trioza litseae* (= *T. eastopi*).

In 1978 *Tamarixia radiata* was introduced from India and released on the leeward (west) side of Réunion. From 1982 onwards *D. citri* has virtually disappeared from commercial citrus orchards, although on *Murraya paniculata* hedges there persist low populations of *D. citri* which are parasitised by *T. radiata* and occasionally, especially at higher altitudes, by *D. aligarhensis*.

The excellent success of these two biological control projects is ascribed to 3 factors:

(i) the absence of hyperparasitoids of the primary parasitoids of *Tamarixia dryi* and *T. radiata*.

(ii) the presence of an alternative host for *Tamarixia dryi*, which enabled it to maintain itself as *Trioza erytreae* populations diminished.

(iii) the maintenance on *Murraya paniculata* hedges of low populations of *D. citri*, heavily parasitised by both *T. radiata* and *D. aligarhensis* (Aubert 1987c; Etienne and Aubert 1980; Quilici 1989).

SAUDI ARABIA AND YEMEN

In Saudi Arabia, both *D. citri* and *Trioza erytreae* are present; the former is the main vector of citrus greening. Both vectors are also present in Yemen where citrus greening at high elevations is probably the African form transmitted by *T. erytreae* (Bové 1986). In Saudi Arabia lime and lemon trees are favoured hosts of *D. citri* (Wooler et al. 1974).

TAIWAN

The nymphal ectoparasitoid *Tamarixia radiata* was introduced from Réunion and, after mass rearing, released widely in citrus orchards and on *Murraya paniculata* hedges from 1984 to 1988. It became established, attaining parasitisation rates of up to 100%. Hyperparasitisation was initially, in 1988, below 1% (Chien 1989; Chien et al. 1988; Su and Chen 1991), but by 1991 had risen gradually to 5.6% (Chien et al. 1991a). This is in contrast with levels of 72% by some 10 species attacking the native *Diaphorencyrtus aligarhensis*. High levels of attack on *D. aligarhensis* is one reason why this species is far less effective against the citrus psyllid than the introduced *T. radiata* (Chien et al. 1988). *T. radiata* was capable of maintaining *D. citri* at low densities in relatively stable habitats where *Murraya paniculata* was occasionally present, whereas *D. aligarhensis* has adapted to unstable habitats. However, it only provides partial control due to 25.5 to 51.1% hyperparasitisation throughout the island. In the Taichung area, *T. radiata* was more abundant than *D. aligarhensis*, but the peak abundance of the two did not overlap and the total parasitisation varied from 80 to 100% from February to April and 32 to 80% for the remainder of the year. Application of methomyl gave good control of *D. citri*, but it reduced parasitisation to a level of 0 to 4%. In an untreated citrus orchard with only 0.1 to 0.4 *D. citri* adults per 10 cm length branch, the parasitoids caused 15.5 to 46.7% parasitisation (Chien et al. 1991a). Citrus greening in Taiwan is known as likubin or leaf mottle disease.

VIETNAM

Tamarixia radiata was found parasitising 3 to 10% of 4th and 5th instar nymphs of *D. citri* and *Diaphorencyrtus aligarhensis* was also present (Myartzeva and Trijapitzyin 1978; Trung 1991; van Lam 1996).

Major natural enemies

HYMENOPTERA

Diaphorencyrtus aligarhensis Hym.: Encyrtidae

This primary endoparasitoid was described by Shafee et al. (1975), from India as *Aphidencyrtus aligarhensis*. Its hosts include *Diaphorina citri*, *D. auberti*, *D. cardiae* and *Psylla* sp. (Qing and Aubert 1990).

The *D. citri* mummy parasitised by *D. aligarhensis* is brownish and hemi-spherical and encloses the parasitoid pupa. The parasitoid emerges from the side of the abdomen. Development from egg to adult takes 18 to 23 days at 25 ± 1°C and 80 to 85% relative humidity (Tang and Huang 1991). No males occur and unmated females produce females. On average, 4.5 eggs are laid per day with an average production of 144 per female. Third and 4th instar *D. citri* nymphs are preferred over 2nd instar, and 1st and 5th instars are not parasitised. Usually only one egg is inserted into each host, but the haemolymph of many young nymphs is consumed leading to their death (Tang and Huang 1991).

Tamarixia radiata Hym.: Eulophidae

This ectoparasitoid was described from India (Waterston 1922) where it is an important species (Husain and Nath 1924). It has been recorded in China (in 1982: Tang 1989), Indonesia (Nurhadi 1989), Malaysia (Lim et al. 1990), Nepal (Lama et al. 1988), Saudi Arabia (Aubert 1984a), Thailand (Qing and Aubert 1990) and Vietnam (Myartzeva and Trijapitzyin 1978). *T. radiata* has been introduced to, and established in, Réunion (Aubert and Quilici 1984), Mauritius (Quilici 1989) and Taiwan (Chiu et al. 1988).

T. radiata was found to be the dominant parasitoid of *D. citri* on *Murraya paniculata* in Fujian, comprising 62.6% of all parasitoids and hyperparasitoids emerging. The second in abundance was the hyperparasitoid *Tetrastichus* sp., most of which were bred from *T. radiata*, an average of 21.8% hyperparasitisation, rising to a maximum of 87.9%, whereas the other primary parasitoid *D. aligarhensis* was hyperparasitised to an average of 34.1% (Tang 1989).

The *T. radiata* female oviposits ventrally between the thorax and abdomen of the nymph, preferably of the 5th instar, and its fully grown larva spins silk to attach itself and its host to the plant substrate. The *D. citri* mummy parasitised by *T. radiata* has a dark brown, flattened body and the parasitoid pupa remains external to, and on the ventral surface of, the host. The adult wasp emerges via a hole cut through the thorax of the host (Qing 1990; Tang and Huang 1991). Under favourable conditions, parasitisation can exceed 90%, as in India (Husain and Nath 1927) and also in Réunion, Nepal and Taiwan (Quilici and Fauvergue 1990).

Male *T. radiata* are capable of multiple matings, but females usually mate only once. The egg to adult period was 11.4 days (egg 1.9, larva 4.0, prepupa 0.6, pupa 4.9 days), females lived 23.6 days and males lived 14.8 days (Chien et al. 1991a,b; Chu and Chien 1991). Fauvergue and Quilici (1991) report reduction of the duration of immature stages with increasing temperature from 17 days at 20°C to 8 days at 30°C. Adult females lived 37 days at 20°C and 8 days at 35°C. Females kill some 80% of *D. citri* hosts by parasitisation and 20% by host feeding. When 40 psyllids were presented per day a female killed 513 psyllids in a lifetime. At an optimum temperature of 25°C, 24, 5th instar nymphs were killed per day (Chien et al. 1993). Adult parasitoids can be cold stored at 8°C for between 46 and 60 days (Chien et al. 1993). Oosorption occurred when hosts were unavailable. This extended the reproductive period, but diminished the total number of eggs laid (Chien et al. 1994b). Feeding by females on the honeydew produced by the host and on host haemolymph provides nutrients for egg production. The parasitoid fed on the exudate of 28% of host eggs parasitised (Chien et al. 1994a). The optimal host density over the entire *T. radiata* lifetime was found to be 2 to 8 per day, of which 90 to 94% were utilised. For the peak oviposition period, optimal density was 2 to 20, of which 87 to 90% were utilised (Chien et al. 1995).

The sex ratio of *T. radiata* is 1:3 in favour of females. Unmated females give rise only to male offspring. Oviposition occurs on 3rd, 4th and 5th instar nymphs and there is discrimination against ovipositing in nymphs containing older *D. aligarhensis* larvae. The average number of offspring is reported as 134 with 6.5 eggs laid per day (Tang and Huang 1991). Observations in China indicate that *T. radiata* is more affected by low temperatures than *D. citri*. Thus *T. radiata* breeds more effectively in Xiamen, where the lowest winter temperature is 3.9°C, than in Fuzhou, where overwintering is jeopardised by lowest minimum temperatures of –2.5°C (Aubert 1990).

Tetrastichus sp. Hym.: Eulophidae

This undescribed species is an important hyperparasitoid of *Tamarixia radiata* in China. Average hyperparasitisation amounted to nearly 25%, with a maximum of 87.9%. The genus *Tetrastichus* contains more than 150 species attacking a wide variety of hosts.

ARACHNIDA

Marpissa tigrina: Salticidae

The number of *D. citri* consumed daily by an individual spider increased with an increase in available prey up to 40. Further increases in prey numbers reduced predation. The results suggest that *M. tigrina* is a highly efficient predator of *D. citri* (Sanda 1991).

Comments

Diaphorina citri and its two primary parasitoids, *Diaphorencyrtus aligarhensis* and *Tamarixia radiata*, are (especially the first two species) very widespread in Southeast Asia. In these countries the prospects for biological control are unpromising, although the careful timing of least harmful, but still effective, insecticides (or, preferably, special petroleum oils) would favour a build up of the parasitoids. The role played by hedges and other plantings of the common, favoured host, jasmin orange, *Murraya paniculata* in encouraging either *D. citri* or its parasitoids is worthy of careful investigation, for this may differ widely according to the insecticidal treatments in the nearby citrus plantings. Overhead irrigation to reduce numbers of eggs and young nymphs during periods of growth flushes is probably uneconomical in most situations, but is possibly a factor to consider in a pest management approach.

Although *D. aligarhensis* appears to be a less effective parasitoid than *T. radiata*, it still may contribute useful suppression of *D. citri* where it can be introduced without encountering hyperparasitoids.

In contrast to much of Southeast Asia, the prospects for successful biological control of *D. citri* appear to be promising for countries that have been recently invaded, particularly if there are few or no hyperparasitoids already present that are capable of attacking *T. radiata* and/or *D. aligarhensis*. In this context it may be valuable to explore the situation in Irian Jaya and Timor where *D. citri* has been recorded only recently. Successful biological control there may slow the spread of *D. citri* into Papua New Guinea, Australia and the oceanic Pacific. Brazil has a range of native psyllids that are attacked by *Tamarixia* spp. so it is possible that there are already hyperparasitoids present that would attack *T. radiata* were it to be introduced.

Since *Tamarixia leucaenae* attacks both *Heteropsylla cubana* and *H. spinulosa*, it would be valuble to know whether *Tamarixia radiata* will also attack *Heteropsylla spinulosa*. This is the psyllid that has been successfully introduced to Papua New Guinea, Australia and some oceanic Pacific countries for the biological control of creeping, sensitive plant, *Mimosa invisa*. If it does attack *H. spinulosa*, there would clearly be a conflict of interest between biological control of *D. citri* and of *M. invisa*, were *Heteropsylla spinulosa* to be considered for the latter. However, at least some species of *Tamarixia* are satisfactorily host restricted and it is quite possible that *T. radiata* is one of them.