Judging from the findings mentioned above, it is certain that the natural spread of *D. citri* and, in turn, that of greening disease are often drastically hindered by discontinuance in the distribution of host plants. In this connection, the evidence of steady spread of the disease and its vector northward in Guangxi Province, China, should be noted [215, 555]. It seems to be necessary to analyze the phenomenon in relation to the vegetative situation there.

Generally speaking, the influence of human beings on the dissemination of greening disease and its vectors is profound. Simultaneous introduction of both disease and vector is not always essential. It is reasonable to assumed that a considerable proportion of the past greening epidemics started from man-made introduction of affected plant material into an area which had been disease-free but already infected with citrus psylloids.

Based on his own survey conducted in 1965 and 1966, SCHWARZ [440] classified the citrus growing areas of South Africa into the following three zones: zone A characterized with a high degree of greening infection and a high population of *T. erytreae*; zone B, intermediate to light infection and a relatively small vector population; and zone C, no natural spread of the disease and the state of the vector that it was absent or occurred sporadically in small numbers. Zone A was located in the Transvaal and some important nurseries were included in the zone. The author pointed out that since a few years before, many young trees that had become diseased in the course of propagation in zone A had been sold to other places in the country. For instance, in zone C of Natal, the infection seen in some orchards was traced by him to trees purchased from nurseries in zone A. He also revealed the evidence of secondary transmission at certain places, where the vector was active, in Natal.

In this connection, the situation of the Cape Province appears to be an interesting topic. When surveyed by SCHWARZ [440], the Eastern and Western Cape belonged to zone C and diseased trees observed in several citrus groves there were ascertained to have originated from nurseries in the Transvaal. Since then, according to VAN DEN BERG et al. [509], the disease has not spread within the province even though high vector populations periodically appeared in some parts of the province. In order to answer the question of whether *T. erytreae* distributed in the Cape is incapable of transmitting greening disease or not, the authors carried out a series of experiments of cross-breeding and disease transmission. However, nothing was detected to prove that the triozid from the Cape differs from that from the Transvaal. They have concluded that theoretically, the disease should have spread in the Cape although the reason(s) why this has not occurred is still unclear.

In Saudi Arabia the greening problem started in the early 1970s with the introduction *D. citri*, and during the following ten to twelve years citrus orchards located in the southwestern part of the country were seriously infected with the disease [67]. In the region concerned citrus trees were mostly grown in oases that were distinctly separated from one another by deserts, so there is no doubt that the spread of the disease and the vector there was mainly due to transportation of citrus plants between oases [67].

During the 1930s, in India, the main areas of citrus growing did not suffer from dieback, whose cause is principally greening disease, and citriculture was prosperous. Stimulated by the success in the industry, acreages of citrus were then largely expanded. Unfortunately, in the process of this expansion a considerable amount of infected plant stock was distributed from unhealthy nurseries and subsequent spread of the disease by the vector took place in all citrus growing districts in the country [157].

In Java, Indonesia, transport of citrus plants from one province to another has been prohibited by the local authorities. As a matter of fact, however, it is difficult to effectively control the villagers' activity of selling their plants, in which ones of dubious origin are included, and consequently the contamination with greening disease and the vector is diffusing widely in the island [44]. It has been pointed out that the spread of the disease was further enhanced by the acquired ability of nurserymen to produce budlings [493].

When the situations in the above-mentioned countries are compared with the Thailand situation, which is characterized by the isolated distribution of the main areas of citrus growing (p. 132) and probably, practically no transport of plant materials from one area to another, it would easily be understood how influential the man-made dissemination of the disease and the vector is.

### 3-4. Monitoring of population processes

Since *Trioza erytreae* nymphs form pits on citrus leave, checking for pitted leaves is a method of estimating populations of this triozid. When more than 50% of flushes were pitted, the infestation was rated as 'heavy' [45, 46]. *Diaphorina citri* nymphs do not leave any clear sign of feeding. In case of such a pest, as pointed out by AUBERT [38], multiplication is apt to be overlooked by farmers and even extension service officers, and therefore development of an adequate technique for monitoring is particularly important from the viewpoint of management of the pest.

AUBERT and QUILICI [45, 46] used adult density as an indicator for infestation of *D. citri*. They rated the adult concentration as 'heavy' when a 5-minute sampling with a mouth aspirator collected 150 adults or more. CATLING [104] adopted visual counting of eggs and nymphs with a hand lens, but this method would be very laborious and be apt to become inaccurate when used under the condition of high population density.

AHMAD [14] treated the whole tree with an insecticide and then counted dead bodies of *D. citri* that fell on a white sheet of paper under the canopy. His purpose was to estimate the population size and the method was not used for monitoring the population process.

Recently, a fluorescent yellow sticky trap has become known as an excellent apparatus for monitoring *T. erytreae*. Starting from the speculation that many monophagous-oligophagous insects may tend to be visual specialist in comparison with polyphagous insects, PROKOPY and OWENS [384c] suggested that visual traps incorporating the synthetic equivalent of comparatively specific host plant visual stimuli should prove useful in monitoring a number of monophagous-oligophagous insect species on crops. SAMWAYS [426] has revealed that *T. erytreae*, an oligophagous species, is strongly attracted to yellow surfaces, particularly fluorescent yellow-green (about 530 nm). A monitoring trap developed by him using 3M Saturn Yellow self-adhesive tape was highly weather tolerant and proved to be a sensitive indicator of the triozid abundance. A practical guide for monitoring by means of this type of trap is given in SAMWAYS et al. [431]. The trap is also effective for the thrips, *Scirtothrips aurantii* Faure, another serious pest of citrus in South Africa.

As compared with visual counts, trap catches were superior in sensitivity at low population densities [426], but not always so at high densities [428].

SAMWAYS [428] has proposed the concept of a double threshold instead of a single threshold. Concretely, the tolerable limit set up for *T. erytreae* is two individuals per set of three traps during each of two consecutive weeks. In South Africa the period between the beginning of July and the end of January is called the 'risk and control period' for the triozid, and whenever trap catches exceed the threshold during this period, it is recommended that chemicals should be sprayed immediately [431]. It is expected that the suppression of the population upsurge in spring and early summer will greatly diminish the risk of chemical spray in later season, the time when natural enemies of the whole complex of citrus pests must be conserved.

According to M. J. Samways (personal communication), citrus orchards in southern Africa are principally under biological control for most arthropod pests and *T. erytreae* and *S. aurantii* are actually the only pests against which use of chemicals is unavoidable when absolutely necessary. In this situation monitoring of the two pests is believed to be a key technique for the accomplishment of pest management in the citrus orchard.

AUBERT [34] recommends that Saturn Yellow traps should be set up beside indigenous rutaceous plants to detect wild reservoirs of *T. erytreae*. He also suggests the significance of comparing trap catches with the density of pits formed by *T. erytreae* nymphs on citrus leaves, because there is sometimes a very fair possibility of confusing adult of this triozid with those of other closely related species caught on the trap.

In Reunion AUBERT and QUILICI [47] collected adult psylloids on the entire canopy of *Murraya paniculata* with a large aspirator named D-VAC machine in order to check the efficiency of the Saturn Yellow trap and an ordinary mouth aspirator by comparing data from these tools with D-VAC machine catches. Since by that time *T. erytreae* had already disappeared in the island due to success in the biological control program, psylloids collected by the authors were all *D. citri*. As the results of the comparison, it was found that trap catches increased with a tendency similar to the rise in D-VAC machine catches but the mouth aspirator was shown to be less accurate than the machine, especially for very low or very high populations.

In mainland China XIA and XU [543] points out that the yellow trap technique is able to reflect partially the flying activity of *D. citri*. In the Philippines GAVARRA and MERCADO [172] recorded only a small number of catches from Saturn Yellow traps located at certain places within the area infected with *D. citri*. It is not long since the trap became known among Asian researchers, so further accumulation of data would be necessary before the technique is established as a practical one in the region.

As suggested by XIA and XU [543], the yellow trap may be useful also for monitoring a complex of natural enemies including *Tamarixia radiata* and other parasitoids.

## 4. Control of *Trioza erytreae* and *Diaphorina citri*, with special emphasis on its importance to citriculture

### 4-1. Biological control

The eulophid parasitoids, *Tamarixia dryi* and *T. radiata*, are biological control agents that have brought about a splendid success in controlling the vectors of citrus greening disease in Reunion Island. In his survey carried out before the introduction of the parasitoids, CATLING [109] found no signs of live indigenous parasitoids or parasitoid mummies of the vectors in the island. Later, ÉTIENNE [145] recorded an encyrtid species from the island but its parasitic activity was quite insufficient (it is guessed that the parasitoid would have been *Diaphorencyrtus aligarhensis* (cf. section 3-2-3)). It is certain that the very poor parasitoid fauna was not as a result of suppression by hyperparasitoids, because even after the imported eulophids mentioned above were released, no problem of hyperparasitism has happened there.

In 1974 adult *T. dryi* and mummified nymphs of *T. erytreae* were imported from the Transvaal, South Africa into Reunion. Then, in 1978, colonies of *D. citri* nymphs including mummies were imported from Punjab, India. In the insectary several kinds of Chalcidoidea emerged from the mummies of both origins, but wasps other than *T. dryi*, *T. radiata* and *Psyllaephagus pulvinatus* (an encyrtid parasitic to *T. erytreae*) were all killed, because they were mostly hyperparasitoids. The three parasitoid species were then multiplied indoors and repeatedly released in the field [145, 146].

Of the two parasitoids released for the control of *T. erytreae*, *P. pulvinatus* failed to establish itself after all but the other, *T. dryi*, settled at once and increased in number so rapidly that the host became very rare throughout the island three years after the commencement of the project. In Reunion, *Trioza eastopi* Orian, another triozid of Asian origin, played an important role as an alternative host of *T. dryi*. This triozid showed a marked preference for breeding to *Litsea chinensis* Jacq, a lauraceous weed shrub commonly seen in the island, and became a reservoir of *T. dryi* after the parasitoid was released [45, 46] (in his article published later, QUILICI [393] has given the name *Trioza litseae* Bordage for the above-mentioned triozid instead of *T. eastopi*).

The activity of *T. radiata* was also conspicuous. By 1980, two years after the commencement of the release of the parasitoid, *D. citri* decreased in number so much as to be hardly seen on citrus. Different from the case of *T. dryi*, *T. radiata* had no alternative host. *D. citri* colonies on *M. paniculata* hedges were reservoirs of this eulophid instead [45, 46]. The following experiment to demonstrate very high efficiency of *T. radiata* was conducted by AUBERT (Fig. 71 in [36]) : in the insectary a large population of *D. citri* established on *M. paniculata* broke down to nearly zero only six months after the introduction of the eulophid into the experimental system.

Release of *T. dryi* was discontinued in January 1976, less than two years after the commencement of its release, but the parasitoid maintained its population by itself and since January 1980, no catch of *T. erytreae* has been recorded in monitoring over the whole island (Fig. 70 in [36]). Total elimination of the triozid from Reunion was thus declared [47].

The duration of release of *T. radiata* was also less than two years. In this release campaign, however, the complete elimination of *D. citri* has not eventuated (Fig. 74 in [36]). The psyllid has been subsisting in scattered residual spots on ornamental *M. paniculata* [47]. *M. paniculata* provides excellent shelter for the psyllid, but owing to the parasitic activity of *T.*

*radiata* in this habitat, *D. citri* does not multiply to such an extent as to cause significant infestation on nearby citrus plantings.

QUILICI [393] mentions the following three main factors that are considered to have contributed to the success of the Reunion biological control program against the greening vectors: (a) the original absence of hyperparasitoids in the citrus-psylloid complex of the island, (b) adaptation of *T. dryi* on an alternative host, *Trioza litseae*, and (c) presence of low *D. citri* populations restricted on *M. paniculata* hedges as reservoirs of *T. radiata*.

Besides those factors, the smallness of the island was likely to be another factor of the success. It can generally be said that as compared with a large island or a continent, a small island is rather simple in topography and agro-ecosystem, so that when it is located far away from the mainland, it is advantageous in attaining overall spread of a biological control agent and preventing invasions of the target pest species from the outside.

Recently, introduction of *T. radiata* has been made from Reunion to certain Asian countries. Transportation to Taiwan was done four times during the period from 1983 to 1986 [128, 128-1, 468]. Except the first trial, when no live wasp was yielded from the material that arrived, the parasitoid was multiplied in the insectary and released at several localities in the island. *T. radiata* has thus been established in Taiwan, but, as mentioned in section 3-2-3, it is attacked by some indigenous hyperparasitoids. If it happens that the impact of the hyperparasitoids becomes stronger in the future, we cannot help thinking that the biological control program by using *T. radiata* in Taiwan will fail to bring about the desired result. In the Philippines the first attempt to introduce *T. radiata* failed to materialize. Efforts are being made to succeed in further trials of introduction as well as to establish the technique for mass-rearing the host, *D. citri* [172].

Import of *T. radiata* and *Diaphorencyrtus* sp. was made from Reunion into South Africa for the purpose of biological control of *T. erytreae*, but the attempt was unsuccessful since they were too specific to attack the triozid [498r].

SAMWAYS and GRECH [429] reported that the fungus, *Cladosporium oxysporum* (Berk. et Curt.), isolated from the mealybug, *Planococcus citri* (Risso), had a considerable initial impact on *T. erytreae* population when applied in the field. It, however, was unable to continue suppressing the triozid population to a great extent. They have concluded that the fungus itself is unsuitable for the control of low-level *T. erytreae* populations, although isolation and development of a possible toxin from it may have economic potential.

Generally speaking, as mentioned in section 3-2-3, the influence of predators on the populations of greening vectors is lower and less stable than that of parasitoids. Nevertheless, any measure for protecting the indigenous predators may be worth thinking about. Concerning the pear psylla, *Psylla pyricola* Foerste, the idea of cover crop manipulation has been proposed by FYE [158c] to encourage a complex of general predators associated with the psyllid in pear orchards.

## 4-2. Chemical control and other techniques proposed for controlling the psylloids

In South Africa, it was during the last few years of the 1950s following the continued use of parathion sprays for the control of red scale, *Aonidiella aurantii* (Mask.), that the infestation with *T. erytreae* became outstanding and crop losses due to greening disease became severe [369]. This evidence suggests the possibility that the natural balance which had presumably existed between the triozid and natural enemies in citrus groves was destroyed by the careless use of such a nonselective, high toxic chemical as parathion.

In the latter half of the 1970s, the development of organophosphate resistance in *A. aurantii* forced South Africa citrus growers to adopt an integrated spray program as quickly as possible. Then, the scale soon became controlled effectively by a complex of indigenous natural enemies, and furthermore, biological control of some other important citrus pests were practically materialized [50]. Under these circumstances *T. erytreae* still remains as a species requiring chemical treatment in that country, although development of the monitoring system appears to offer a promising prospect for further improvement of chemical spray programs against it (cf. section 3-4).

The systemic insecticides, dimethoate and monocrotophos, were found to be highly effective against *T. erytreae*. In field spray tests a concentration of dimethoate as low as 0.0025% active ingredient proved to be sufficient to kill eggs and nymphs [99] and 0.001-0.005% monocrotophos brought about a satisfactory result of controlling nymphs [79r].

SCHWARZ and VAN VUUREN [461] proposed a technique of trunk injection with tetracycline hydrochloride in order to reduce the incidence of greening disease. As is well known, the antibiotic is unable to eliminate the greening pathogen. However, because of its high effect of suppressing the expression of greening symptoms, the trunk injection technique became popular in South Africa. SCHWARZ et al. [458] then conducted a preliminary trial of simultaneous trunk injection with tetracyclines and insecticides, in the latter of which dimethoate and monocrotophos were included. In the trial no combination of the antibiotics and insecticides tested exhibited phytotoxicity and monocrotophos was concluded to be most promising among the insecticides tested.

Even before the 1970s tree trunk injections of systemic insecticides including dimethoate were practised or tested in forest entomology [365c]. However, the results obtained by SCHWARZ et al. [458] would be the first successful demonstration of the combination of antibiotics and systemic insecticides in trunk injection. According to them, insecticide injections cannot entirely replace spraying for the control of *T. erytreae*. SCHWARZ [451] describes that when systemic insecticides are injected into citrus trunks with antibiotics at the time of flushing, they can drastically reduce the triozid population without exerting any adverse effect on the fauna of natural enemies in the citrus grove.

Besides trunk injection with systemic insecticides, a variety of methods for chemical control of *T. erytreae* with least adverse effects on natural enemies of citrus pests have been developed in South Africa. Among them there are soil application of dimethoate (for instance, MOLL and VAN VUUREN [340]) and application of granules containing aldicarb on the trunk surface [83r]. BUITENDAG and DREYER [86] point out disadvantages of the techniques of soil application and trunk injection, and instead propose the following two new methods of trunk application: 'paint brush application' and 'spray application' using Azodrin 40, a preparation of monocrotophos registered for trunk application, as the chemical. Since the latter method can be performed by using a specially designed applicator that is expected to reduce the chance of the operator's contact with the insecticide, it is believed to be relatively safer than the former [86].

There are a fairly large number of reports showing the sensibility of *D. citri* to dimethoate, monocrotophos and some other systemic insecticides (for instance, KOLI et al. [261]). In the Philippines, CATLING [99] was alarmed at observing frequent sprays of endrin, parathion and other broad-spectrum insecticides in some large citrus plantings, and recommended that an integrated approach to citrus pest control should be taken instead, mentioning dimethoate as one of selective insecticides to be considered in a possible integrated control system. In Indonesia soil application of dimethoate by means of drenching and spot application of monocrotophos on bark are under investigation as techniques for avoiding the adverse effect of chemicals on beneficial insects in citrus canopies [531]. Bark treatment with monocrotophos was also tested in Taiwan [491r].

Recently, we have read some reports on trials for developing new methods without depending on insecticides. WU and FAAN [540] have reported a noticeable function of China berry seed oil as an antifeedant for *D. citri* in the laboratory. SAMWAYS and MANICOM [430] have presented an idea of using heavily-pruned Valencia sweet oranges (*Citrus sinensis*) as trap trees for *T. erytreae*. Although no positive result was yielded, SAMWAYS [426] tried field experiments of mass-trapping under a combination of trap trees with yellow sticky stripes (cf. 3-3). GAVARRA and MERCADO [172] have suggested a possibility of using the Rutaceae, *Clausena anisum-olens* Merr., as a trap for *D. citri*, because the plant was found by the authors to attract the psyllid adults but not stimulate their oviposition.

## 4-3. Vector control as a component of greening disease prevention strategies

Any action against the greening pathogen is not effective under the condition of high density of the vector insects. It is evident, at the same time, that the greening problem cannot be solved only by vector control, however effectively it is performed. To correctly arrange the vector control program in a greening prevention strategy is therefore of critical importance.

In South Africa, when the evidence of artificial dissemination of the disease was clarified (cf. section 3-3), a regulation was established to prohibit the movement of citrus trees from one province to another [317]. The same kind of regulation has also been put into force in Asian countries. For instance, a decree issued in 1985 by the Indonesian government concerning the domestic quarantine of greening disease regulates strictly the movement of citrus plant materials within the country, prohibiting transport of any material without a label for disease-free certification [387]. The problem is how effectively the local authority should prevent the illegal leak of plant materials from private nurseries as mentioned by AUBERT et al. [44]. It will take some considerable time before a practical solution is found to the problem in the respective Asian countries concerned.

BUITENDAG [80] classifies the current trend in greening control into the two parts, a preventive approach and a corrective approach. His discussion seems to reflect the present status of citriculture in South Africa, and has no mention of the problems on plant quarantine and supply of healthy plant materials probably because these problems have already been settled in that country.

Buitendag's preventive approach consists of the following two components: control of the vector and use of greening resistant or tolerant citrus. In South Africa chemical control of the vector, *T. erytreae*, is likely to be the most acceptable approach to greening control. On taking this approach, he emphasizes, one must have a keen interest in preventing any adverse effect on the natural balance in the citrus groves by means of, say, adoption of such a technique as trunk treatment with Azodrin 40 (cf. the preceding section). As for the aspect of plant breeding, BUITENDAG [80] suggests that a possibly tolerant navel orange selection is being tested.

The corrective approach is taken first of all from the viewpoint of reducing the greening inoculum. Concrete measures mentioned in this regard are, for example, removing heavily infected young trees and cutting off infected branches from older trees. Another aspect of the approach is to reduce yield losses by means of suppression of greening fruit symptoms. At present it is achieved only through the trunk injection of antibiotics. As a chemical to be used BUITENDAG [80] recommends rolitetracycline (PMT), which is, according to BUITENDAG and BRONKHORST [82], easier to handle and less phytotoxic than tetracycline hydrochloride. Trunk injection, however, is time consuming, costly, and, especially, not a technique aiming at the elimination of the pathogen, so BUITENDAG [80] does not rate it very high as a technique supporting the current trend in greening control.

In Thailand SCHWARZ et.al. [456] recommended, on one hand, removal of affected trees in areas with low incidence of greening disease and, on the other hand, growing of relatively tolerant local varieties under isolated and vector-controlled circumstances in areas with high greening incidence.

A variety of greening control programs have been presented by researchers from different Asian countries. However, there seems to be a similarity among them. Mainly based on ZHAO [554], the skeleton of the programs is summarized as follows :

a) Efficient foreign and domestic plant quarantine

b) Establishment and propagation of disease-free plant materials

c) Development of healthy plantings under sanitary conditions

d) Monitoring and control of the insect vector

Concerning item b), a technique of combined thermotherapy and shoot tip grafting has recently been developed to obtain clean budwood [40, 183]. The treatment, however, is not perfect, so post-indexing is essential [40].

Different from the aphid vectors of citrus tristeza virus disease, which are characterized by a wide-range dispersal of alate forms, the psylloid vectors of greening disease are fairly easily restricted their distribution under the condition of discontinuance in host plant distribution (cf. section 3-3). It is not always difficult, therefore, to create greening-free circumstances and maintain them even within an area under the influence of the vectors. QIAN [391] has presented excellent examples of disease-free nurseries established in an isolated hilly area and a citrus farm completely rehabilitated from heavy contamination with the disease.

It is almost certain that replantation of young trees without isolating the plantings from the surroundings does not yield good result because vigorous flushing of young trees tends to strongly attract vector insects from nearby affected trees. Treatment of neglected citrus trees and alternative hosts of