

The eradication projects and preventative control of quarantine pests in Okinawa, Japan

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ABSTRACT

Of the several exotic insect species in Japan, five quarantine plant pest taxa: the oriental fruit fly, *Bactrocera dorsalis* complex, the melon fly, *Zeugodacus cucurbitae*, the solanaceous fruit fly, *Bactrocera latifrons*, the sweet potato weevil, *Cylas formicarius*, and the West Indian sweet potato weevil, *Euscepes postfasciatus*, have been targeted in eradication programs using the male annihilation technique (MAT) and/or the sterile insect technique (SIT). Although all targeted fruit flies have successfully been eradicated, the incidences of re-invasion by *Bactrocera dorsalis* complex have been increasing in recent years, indicating the necessity for reinforcement and improvement of countermeasures for fruit fly re-invasion and/or recolonization. The program targeted at *C. formicarius* achieved the goal of complete eradication in Kume Island. The program for *E. postfasciatus* has yet to achieve eradication, even though it was initiated at the same time as that for *C. formicarius*. Major technical improvements are required for successful eradication of *E. postfasciatus*.

Keywords: sterile insect technique, male annihilation technique, *Bactrocera dorsalis*, *Zeugodacus cucurbitae*, *Cylas formicarius*, *Euscepes postfasciatus*

INTRODUCTION

Okinawa is located in the southernmost part of Japan, between Kyusyu and Taiwan. Many exotic insects have invaded Okinawa, some of which are now established in this

subtropical region^(16, 18). These invasive insects include some serious quarantine plant pests, and the transport of their host plants from an infested area to the non-infested areas is prohibited. These taxa are capable of inflicting significant economic damage on the agricultural product marketing. Therefore, eradication programs targeting these pests have been conducted in Okinawa, using the sterile insect technique (hereafter, SIT) and/or the male annihilation technique (hereafter, MAT) (Table 1). SIT is an environment-friendly behavioral method⁽⁷⁾, wherein a large number of insects are produced, sexually sterilized, and released into the field. The released infertile males compete with the wild males for mating with wild females, resulting in reduction of the wild population via production of sterile eggs⁽¹⁷⁾. MAT is a target-specific chemical method, where a mixture of male attractant and insecticide is dispersed in the field, resulting in decrease of wild male abundance and the loss of mating opportunities for wild females⁽⁶⁰⁾. Two pest taxa, the oriental fruit fly *Bactrocera dorsalis* complex⁽⁶⁾, and the melon fly, (*Zeugodacus cucurbitae* (Coquillett) were eradicated in Japan by 1985 and 1993, respectively^(14, 20, 25, 26). Two other quarantine pests have been successfully eradicated in selected areas. The Solanaceous fruit fly, *Bactrocera latifrons* (Hendel), was eradicated from Yonaguni Island by 2011 using SIT^(8, 19), while the sweet potato weevil, *Cylas formicarius* (Fabricius), was successfully eradicated from Kume Island by 2012 using SIT and MAT⁽³³⁾. On the other hand, the eradication programs for the West Indian sweet potato weevil, *Euscepes postfasciatus* (Fairmaire) using SIT started in Kume Island and Tsuken Island in 1995 and 2007, respectively^(27, 28, 49), but the eradication goals have not yet been achieved, mainly due to limited production of sterile weevils⁽⁴¹⁾.

In this paper, we report the process followed during successful pest eradication programs. We also discuss the risk of re-invasion after eradication, and the counter-measures against them. Finally, we report a current improvement in the mass-rearing system of *E. postfasciatus*, which has been a limiting factor in its eradication program.

Invasion history of and eradication program for *Bactrocera dorsalis* complex and risk of its re-invasion

The oriental fruits fly and its relatives, *Bactrocera dorsalis* complex⁽⁶⁾, include several serious pests of fruits and vegetables⁽²⁾. The history of invasion and eradication of *B. dorsalis* complex in Japan is summarized in Fig.1. Here, we also show the cases

of Amami Islands (Kagoshima Prefecture) and Ogasawara Islands (Tokyo). *B. dorsalis* complex was first recorded on Okinawa Islands in 1919⁽³⁶⁾, on Ogasawara Islands in 1925⁽⁴⁰⁾, and on Amami Islands in 1929⁽⁵⁶⁾. The eradication program in Amami Islands, using MAT with methyl eugenol as an attractant, begun in 1968, and the eradication was confirmed by Japanese Government in 1980⁽⁶⁴⁾. In Ogasawara Islands, the eradication program with MAT started in 1975 and the fruit flies were eradicated in 1983 with the assistance of SIT⁽⁴⁰⁾. In Okinawa Islands, the eradication program using MAT was initiated in 1977 and eradication was achieved in 1985^(20, 21).

However, several re-invasion events have been detected in Okinawa with the help of monitoring traps (hereafter, trap) baited with methyl eugenol⁽²⁴⁾. Ohno et al⁽⁴³⁾ reported that more than 300 adult flies were captured by the traps from 1987 to 2008, showing frequent re-invasions even after the eradication. In fact, the numbers of the male captured by the trap and the incidences of recolonization (i.e., detection of infested fruit) have been increasing in Sakishima Islands, especially after 2010 (Fig. 2). During this period, recolonization occurred ten times (Fig. 2).

One of the possible sources of re-invasion is windborne immigration from distribution areas adjacent to Okinawa, such as Taiwan, the Philippines, and mainland China⁽⁵⁴⁾. Summer is considered the season with high risk of re-invasion by wind in Okinawa Islands and Sakishima Islands^(4, 43, 54).

To quickly counter the re-invasion, we implement two ways of monitoring measures: i) trap survey, where c.a. 500 traps are checked every two weeks, and ii) a biannual host fruits survey, where c.a. 100,000 fruits are collected and inspected. As a preventive control, pieces of wood fiber boards (hereafter, fiber board) soaked with a mixture of methyl eugenol and insecticide are placed in the area four times a year (in total, 400,000 pieces/year).

In all cases of recolonization, the fruit flies were re-eradicated within a few months, using extra countermeasures^(32, 44, 51). A mixture of protein bait and insecticide were sprayed within a 100- to 200-m radius from the point where infested fruits were detected, host fruits within a 500-m radius were removed, and extra pieces of the fiberboard were distributed within a 2-km radius, at a density of 2–3 pieces per hectare.

As seen above, the risk of re-invasion and recolonization of the oriental fruit fly has been increasing in Okinawa. This indicates the necessity for reinforcement and

improvement of countermeasures for controlling the fruit fly re-invasions and/or recolonizations.

Invasion history of and eradication program for the melon fly, *Zeugodacus cucurbitae* (Coquillett), and risk of its re-invasion

The melon fly, *Zeugodacus cucurbitae* (Coquillett), is distributed widely in temperate, tropical, and sub-tropical regions of the world, with India considered its native area ⁽⁵⁾. The fly has been reported to cause damage to 81 host plants, and is a major pest of cucurbitaceous vegetables, particularly bitter melon (*Momordica charantia*), muskmelon (*Cucumis melo*), and snake gourd (*Trichosanthes anguina*) ^(31, 35).

The history of invasion and eradication of *Z. cucurbitae* in Japan is summarized in Fig.3. Here, we also show the cases of Amami Islands (Kagoshima Prefecture). The melon fly was first discovered in the Yaeyama Islands in 1919 ⁽³⁶⁾, and 10 years later, it was reported in the Miyako Islands ⁽²³⁾. In 1970, it was discovered on Kume Island ⁽⁵⁹⁾, and it spread to Okinawa Islands in 1972 ⁽¹¹⁾. It further expanded its distribution to Amami Islands in 1974 ⁽²³⁾.

Prior to the start of the melon fly eradication project, an experimental SIT project was started on Kume Island in 1972 ⁽¹²⁾. Following the successful eradication project on Kume Island, an eradication project for the entire Okinawa Prefecture was initiated in 1979 ^(14, 21). By releasing more than 200 million sterile flies per week, the eradication on Miyako Islands, Okinawa Islands, and Yaeyama Islands was achieved in 1987, 1990, and 1993, respectively ⁽⁴⁾.

As Okinawa is located near South East Asia, where the melon fly currently occurs (i.e., Taiwan), there is always a risk of re-invasion. To prevent re-colonization by accidental invasion from infested areas, the preventive release of 45–70 million sterile flies per week is being carried out continuously. The monitoring has been conducted in the same way as the oriental fruit fly. So far, only a few cases of re-invasion have been detected on the Yonaguni Island. Single male each was caught by monitoring trap in 1993, 1995, and 1996, and a female emerged from a fruit collected in regular host plant survey (Table 2).

Eradication of the solanaceous fruit fly, *Bactrocera latifrons* (Hendel), from Yonaguni Island

The solanaceous fruit fly, *Bactrocera latifrons* (Hendel), is known as a serious pest of solanaceous crops ⁽⁶⁶⁾. It is widely distributed throughout South and South-East Asia ⁽⁶⁶⁾, and has invaded Hawaii ⁽⁶⁵⁾ and Africa ⁽³⁾. In Japan, it was first detected in Yonaguni Island, located in the westernmost part of Japan (only 100 km apart from Taiwan) in 1984 ⁽¹⁵⁾. Since there was a concern that *B. latifrons* could spread over the southern islands of Japan by hitchhiking, transportation of infested fruits, and/or the dispersion of adult flies, eradication project for *B. latifrons* using SIT was urgently implemented in 2004. Firstly, protein bait spray and clean culture methods (removing the host fruit) were applied, to suppress the wild population before implementation of the SIT. Mass release of sterile flies was initiated in 2007. About 400,000 sterilized insects were released throughout the island every week. The last detection of wild *B. latifrons* was in March 2009 in a host fruit survey ⁽¹⁹⁾. The Japanese Government confirmed the eradication of *B. latifrons*, based on the surveys of host fruits in 2011 ⁽⁸⁾. To check the re-invasion in Yonaguni Island, the host fruits are surveyed two times per year. After the eradication, no fruit infested by *B. latifrons* was detected in the island until 2017.

Invasion history of and eradication program for the sweet potato weevil, *Cylas formicarius* (Fabricius), from Kume Island, Okinawa, Japan

The sweet potato weevil, *Cylas formicarius* (Fabricius), is a destructive pest of sweet potato, *Ipomoea batatas* (L.) Lam. ⁽⁶⁷⁾. It also infests wild convolvuaceous plants, such as blue morning glory, *I. indica*, and beach morning glory, *I. pes-caprae*, in Japan ⁽³⁷⁾. The weevil is distributed in subtropical and tropical area of the world ^(55, 62), including the Ryukyu Islands ⁽⁶⁹⁾ and Ogasawara Islands ⁽⁵⁶⁾. The weevil is assumed to have originated from the Indian subcontinent ⁽⁶⁷⁾ or northwestern South America ⁽¹⁾. In Japan, the weevil was first recorded on Okinawa Island ⁽⁵⁶⁾. It was also detected on the Yoron Island and Amami-Oshima Island in 1915, and on the Kikai Island in 1940 ⁽⁵⁶⁾.

The eradication project for the weevil using MAT and SIT was initiated on Kume Island in 1994 ^(27, 28). To suppress the wild population of the weevil to the level at which SIT was applicable, MAT was first applied from 1994 to 1999 ⁽²⁸⁾, wherein fiberboard soaked with a mixture of synthetic sex pheromones ⁽⁹⁾ as a male attractant and insecticide ⁽⁵⁷⁾ was used. Eight-to-sixteen fiberboards were distributed per hectare per

month over the Kume Island, except over meadows and catchments⁽²⁸⁾. The release of sterile weevils was initiated in 1999⁽²⁸⁾. With the progress of the project, the number of released sterile weevil was increased from 30,000 to 500,000 per week, because of the expansion of the productive capacity of the mass-rearing facility⁽²⁸⁾. To evaluate the control efficacy, traps with synthetic sex pheromones were used as an attractant⁽⁶¹⁾, and the host plant stems were examined^(28, 33). To assess the infestation rate, we collected the stems of host plants (*I. batatas*, *I. pes-caprae*, and *I. indica*), dissected them, and counted the number of larvae, pupae, and adults of the weevil therein. The wild weevil was last detected in the island in 2012⁽⁵²⁾. Based on the host plant surveys, the Japanese Government confirmed the world's first eradication of this pest weevil using SIT in 2012⁽³³⁾. After the eradication, the weevil has not been detected in either host plant surveys or monitoring traps until 2017. The weevil eradication program started in 2007 is still going on in Tsuken Island⁽⁴⁹⁾.

Invasion history of and eradication program for the West Indian sweet potato weevil, *Eusepeus postfasciatus* (Fairmaire), and improvement of mass-rearing system

The West Indian sweet potato weevil, *Eusepeus postfasciatus* (Fairmaire), is one of the serious pests of sweet potato, *I. batatas*, in the South Pacific, Caribbean basin, and some countries of Central and South America⁽⁵⁵⁾. The weevil has established throughout Ryukyu Islands (Okinawa Prefecture) and the Amami Islands (Kagoshima Prefecture) after World War II^(56, 69). The eradication program for *E. postfasciatus* using SIT was initiated on Kume Island in 1994⁽²⁸⁾ and on Tsuken Island in 2007⁽⁴⁹⁾.

In Kume Island, the number of the released weevil was increased to about 3,000,000 per week by 2004⁽⁴¹⁾, but was drastically reduced later due to a decreased production of the weevil, which was mass-reared on sweet potato roots^(30, 41). As a cause of the decline, Morita et al.⁽³⁴⁾ found that almost all mass-reared weevils were infected with an undescribed neogregarine *Farinocytis*-like protozoa (*Farinocystis* sp.) which reduces longevity and fecundity of the weevil⁽²⁹⁾. Since it was difficult to eliminate the protozoa from the mass-reared strain of the weevil being reared on sweet potato roots, a novel mass-rearing system was developed using an artificial diet. In this system, the weevil eggs are washed and disinfected before being inoculated on the artificial diet, which is considered free from the protozoa^(29, 42, 58). However, protozoan infection has

not been completely eliminated in the artificial diet system ⁽³⁹⁾. Moreover, as the productivity of the artificial diet system was not enough to replace the sweet potato root system, a combination of both systems has now been adopted (Fig. 4). Recently, a rearing method to reduce the horizontal transmission of *Farinocystis* sp. between adult weevils was developed ⁽⁶³⁾. The reformation of the ingredients of the artificial diet ⁽³⁸⁾ and egg-inoculation density ⁽¹⁰⁾ also helped improve the quantity and quality of the weevil. Owing to these developments, the number of sterile weevil release has recovered to the level of about 1,500,000 per week at present ⁽⁵³⁾. However, this number is still considerably lower than the desirable number of weevils for release, in both Tsuken Island and Kume Island. Thus, the release has been suspended in Kume Island ^(30, 50), and the release program is currently running only on Tsuken Island, the area of which is much smaller than that of the Kume Island ⁽⁵⁰⁾. Clearly, further improvements in the mass-rearing system are necessary to achieve sufficient quantity and quality of mass-reared weevil for the SIT program in Kume Island.

Future prospects

All target fruit flies have been successfully eradicated; however, the incidences of re-invasion of *B. dorsalis* complex have been increasing in recent years. While all these incursions have been controlled within several months, the risk of re-invasion by these species would further increase because of the ongoing climatic change and increasing opportunities of human travel and goods movement. Therefore, we may have to consistently revise and upgrade the trap and the countermeasures for these fruit flies.

Eradication of *C. formicarius* from Kume Island took 19 years, which is much longer compared with the case of the melon fly. This indicates that the required costs (time, money, and manpower) for the eradication of *C. formicarius* are much higher than those for fruit flies. It goes without saying that the eradication program for *E. postfasciatus* is still ongoing, even though it was initiated at the same time as that of *C. formicarius*. Therefore, it is essential to keep improving the techniques used in the eradication programs and revise the strategy for the programs based on these improvements.

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Table 1. Quarantine pest eradication projects in Japan

Target Pests	Area	Period	Methods	References
The oriental fruits fly and its relatives <i>Bactrocera dorsalis</i> complex	Okinawa	1977 – 1985	MAT	Koyama et al. (1985)
	Amami Isls.	1968 – 1980	MAT	Ushio et al. (1982)
	Ogasawara Isls.	1975 – 1984	MAT and SIT ^a	Ohkawa (1985)
The melon fly <i>Zeugodacus cucurbitae</i> , (Coquillett)	Okinawa	1975 - 1993	SIT	Kuba et al. (1996)
	Amami Isls.	1985 - 1987	SIT	Koyama (1994)
The solanaceous fruit fly <i>Bactrocera latifrons</i> (Hendel)	Yonaguni Is.	2004 - 2011	SIT	Kohama & Matsuyama (2010) Fukugasako & Okamoto (2012)
The sweet potato weevil <i>Cylas formicarius</i> (Fabricius)	Kume Is.	1994 - 2012	MAT and SIT	Matsuyama (2010)
	Kikai Is.	2001 -	SIT	Yamaguchi et al. (2010)
	Tsuku Is.	2007 -	MAT and SIT	Okinawa Prefecture (2008)
The West Indian sweet potato weevil <i>Euscepes postfasciatus</i> (Fairmaire)	Kume Is.	1995 -	SIT	Kuba et al. (2005)
	Tsuku Is.	2007 -	SIT	Okinawa Prefecture (2008)

^a SIT was applied to complement MAT in Ogasawara Islands.

Table 2. Record of re-invasion for *Zeugodacus cucurbitae*, (Coquillett) after eradication in Okinawa Prefecture, Japan.

Locality	Period	Method	No. of fly	Reference
Okinawa Is.	1993. Sep. 30-Oct. 14	Surveillance trap	1 male	Okinawa prefecture (1993)
Yonaguni Is.	1995. Jun. 30-Jul. 14	Surveillance trap	1 male	Okinawa prefecture (1995)
Okinawa Is.	1996. Jun. 20-Jul. 4	Surveillance trap	1 male	Okinawa prefecture (1996)
Yonaguni Is.	2004. Jun. 8-Jul. 29	Host fruits survey*	1 female	Okinawa prefecture (2005)

*Emergred from a cherry tomato, *Solanum Lycopersicum* L.

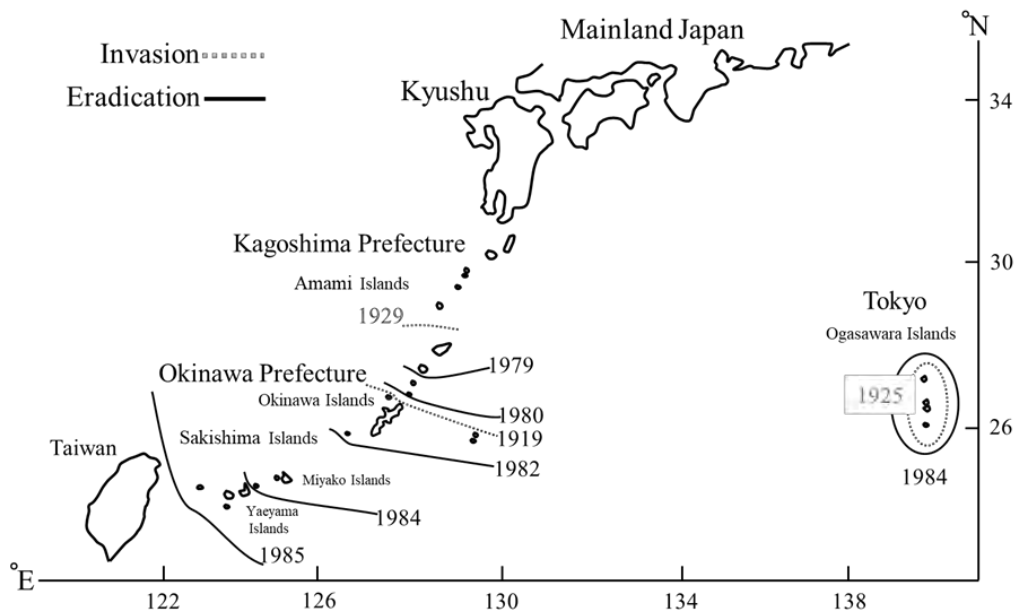


Fig. 1. Invasion and eradication of *Bactrocera dorsalis* complex in Ryukyu Islands and Ogasawara Islands, Japan.

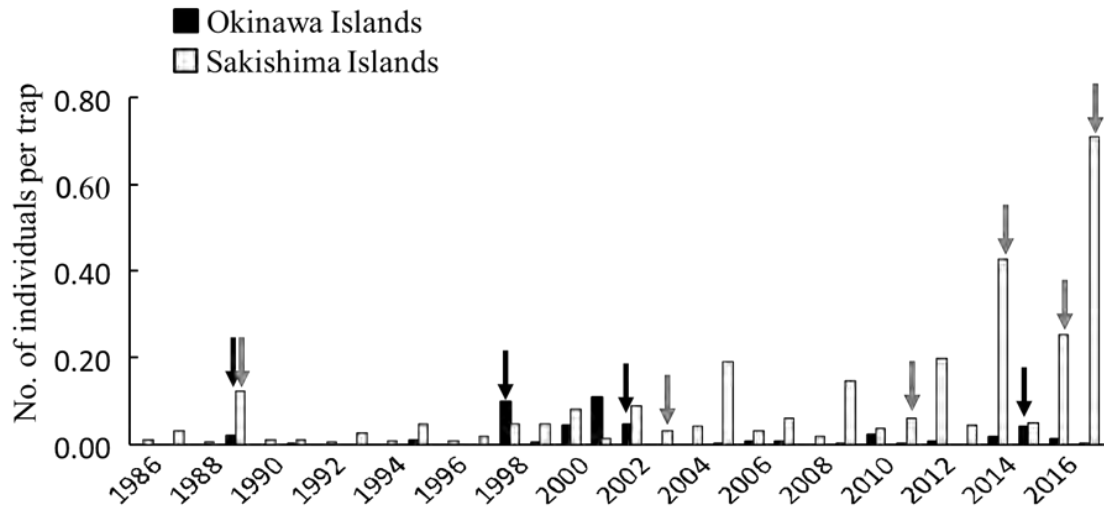


Fig. 2. Records of *Bactrocera dorsalis* complex males captured by surveillance trap in Okinawa and Sakishima Islands. For the male attractant, methyl eugenol (ME) alone was used from 1986 to 1990, while a mixture of ME and cue-lure (male attractant of *Zeugodacus cucurbitae*) with 9:1 blend has been used since 1991. Black and Gray arrows show detection of infested fruits in Okinawa and Sakishima Islands, respectively.

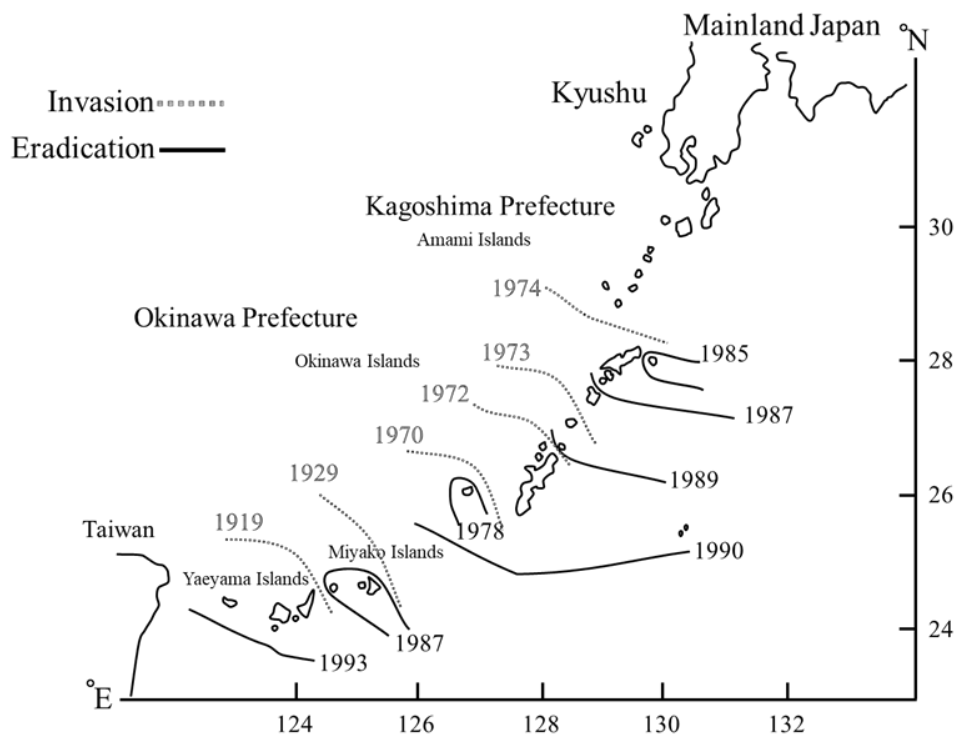


Fig. 3. Invasion and eradication of *Zeugodacus cucurbitae* in Ryukyu Islands, Japan.

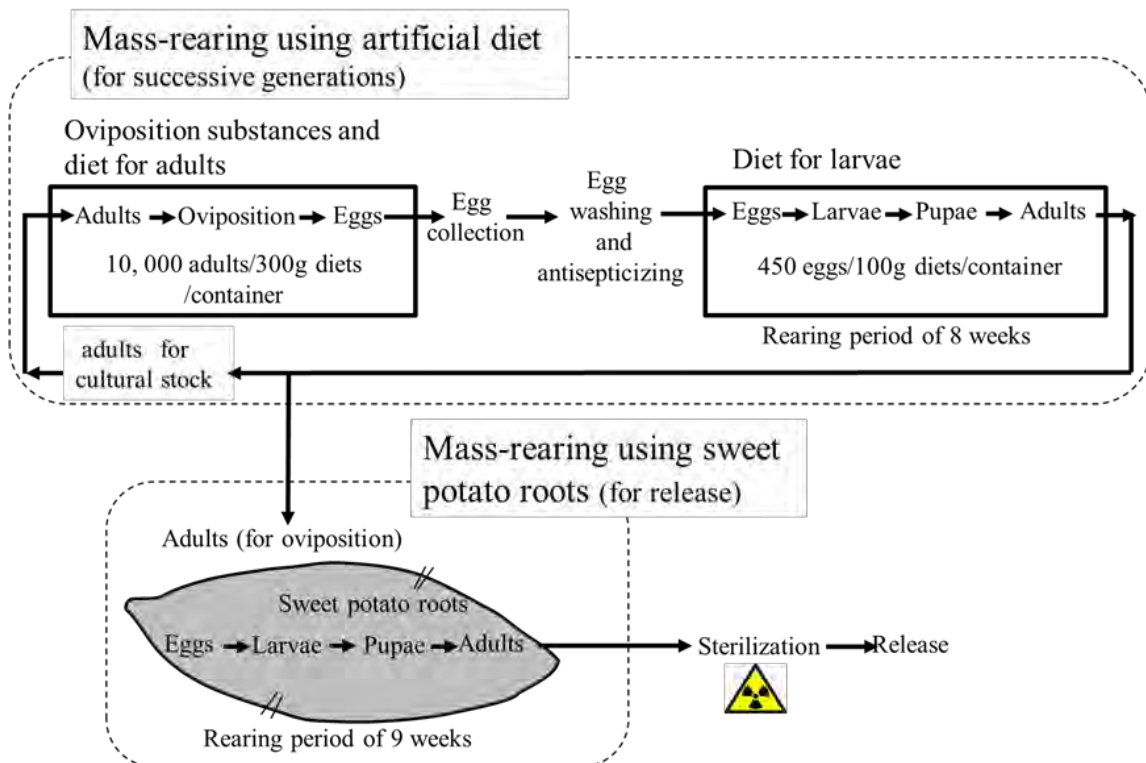


Fig. 4. Schema of the mass-rearing methods of *Eusepes postfasciatus*. Modify the figure of Ohishi et al. (2016).