CLASSICAL BIOLOGICAL CONTROL OF THE CHESTNUT GALL WASP IN JAPAN

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INTRODUCTION

The chestnut gall wasp, *Dryocosmus kuriphilus* Yasumatsu (Hymenoptera: Cynipidae), which is thelytokous and univoltine, is now considered to have been accidentally introduced to Japan from China (Oho and Umeya, 1975). It was found in Okayama Prefecture, in western Japan, for the first time in 1941 (Shiraga, 1951; Oho and Shimura, 1970) and described later as a new species (Yasumatsu, 1951). The adult emerges over a relatively limited period in early summer, and after emergence the female immediately lays eggs inside chestnut buds that will develop during the next spring. Hatched larvae remain immature in the buds and hibernate. When the buds start to develop, the larvae resume their growth, and the buds turn into galls rapidly (Tamura, 1960; Ôtake, 1980, 1989). As a result, the yield of chestnuts from infested trees is reduced, and heavy infestation often causes fatal damage to the trees.

The pest spread so fast after World War II that it had become distributed throughout most of Japan by the end of the 1950s (Oho and Shimura, 1970). Since the larva of the chestnut gall wasp is protected by the thick wall of the gall, no method of chemical control can prevent serious damage to chestnut production. The use of chestnut gall wasp-resistant chestnut varieties was, at first, very effective (Kajiura and Machida, 1961). However, by 1960 galls began to appear, even on formerly highly resistant varieties, and pest abundance increased rapidly again in the 1970s (Shimura, 1973). Based on an analysis of the isozyme pattern of the chestnut gall wasp populations, it was suggested that a biotype of the chestnut gall wasp that can attack the resistant varieties had proliferated and become dominate (Shimura, 1972). Thus, the chestnut gall wasp became one of the most intractable pests of chestnut in Japan (Shiga, 1997).

In 1975, the late Dr. N. Oho found galls of the chestnut gall wasp in China (Oho and Umeya, 1975), and Dr. Y. Murakami learned in 1979 that the wasp had been recorded much earlier in China than in Japan (Murakami, 1980). These findings offered the possibility that the chestnut gall wasp could be controlled, using natural enemies imported from China. With collaboration between Japanese researchers and those from the Chinese Academy of Agricultural Sciences, a Chinese torymid, which was described later as *Torymus sinensis* Kamijo (Hymenoptera: Torymidae) (Kamijo, 1982), was introduced into Japan (Murakami *et al*., 1977, 1980). It was then released in Ibaraki Prefecture in eastern Japan and Kumamoto Prefecture in southwestern Japan.

This report focuses on the case of Ibaraki Prefecture. We first discuss the indigenous Japanese parasitoids of the chestnut gall wasp that were recorded in the prefecture before the introduction of *T. sinensis*. Then, we discuss the introduction, establishment, and expansion of the geographic range of the parasitoid, followed by a discussion of the relationship between *T. sinensis* and *Torymus beneficus* Yasumatsu et Kamijo, the latter species being an indigenous parasitoid related closely to the former.

MATERIALS AND METHODS

Indigenous Parasitoids of *Dryocosmus kuriphilus* in Ibaraki Prefecture

In early spring, withered galls of the chestnut gall wasp, in which the parasitoids had overwintered, were collected mainly at the National Institute of Fruit Tree Science (NIFTS), Tsukuba, in southern Ibaraki Prefecture, about 50 km northeast of Tokyo. They were kept under outdoor temperature conditions so that the adult parasitoids could be observed as they emerged in spring. Fresh galls were also collected in the same area in early summer so that the adult parasitoids could be observed as they emerged later in that season. Observations of the spring collections were carried out in 1979-1982 and of the summer collections in 1978-1981.

Introduction of *Torymus sinensis* to Japan

After the first and preliminary introduction of *T. sinensis* from China in 1975 (Murakami *et al*., 1977), Dr. Y. Murakami brought to Japan 2,609 galls of the chestnut gall wasp with parasitoid larvae that had been collected in Hebei Province, China, in August 1979 with special permission for importation granted through the Plant Protection Law of Japan. Thereafter, a third introduction was made by M. Shiga, one of the present authors, who visited Hebei Province again in November 1981 and imported 2,706 galls into Japan. All of these importations were made by courtesy of the Chinese government.

Release of *Torymus sinensis*

In April 1982, females were selected from among the offspring of the second (1979) introduction; since then, further offspring have been propagated by the bagging method (Ôtake *et al*., 1984). Also in April 1982, the adults of the third (1981) introduction emerged from the galls. Those females were kept in glass tubes for at least two days–enough time to mate with males. Drops of honey were supplied in the tubes. Then, 260 females were released onto 11 wild Japanese chestnut trees (*Castanea crenata* Sieb. et Zucc.) growing on the grounds of the northernmost part of the research station (NIFTS) in Tsukuba, Japan.

Emergence and Distribution Range of Parasitoids

In March 1983, withered galls that had formed in the preceding year at the research station (NIFTS) were collected in all the areas where wild chestnut trees grew naturally among pine and other kinds of trees and shrubs, and some areas where chestnut cultivars had been planted. In particular, all the galls were collected near the point where the parasitoid, *T. sinensis*, had been released in 1982. After 1984, the chestnut gall wasp galls were collected between January and March every year in the same areas as in 1983.

To monitor how the *T. sinensis* population expanded its geographic range after its release at the research station (NIFTS), withered galls were also collected at various localities in the Kanto district (including areas near NIFTS), as well as in the districts of Chubu and Tohoku, from 1983 to 1992. All the galls thus collected were kept in shelters set up outdoors in order to observe the emergence of adult parasitoids under natural conditions.

Infestation Rate of *Dryocosmus kuriphilus*

The effect of the 1982 release of *T. sinensis* on the chestnut gall wasp population was evaluated by observing gall formation on chestnut trees. In 1984, 20 one-year-old twigs from each of 13 naturally growing chestnut trees at the research station (NIFTS) were examined for shoot infestation. The ratio of infested shoots to the total number of shoots examined was regarded as an indicator of the size of the chestnut gall wasp population at the release location. Every year thereafter through 1992, the gall formation rate was monitored from twigs of these 13 trees.

Experimental Crossing among Torymids

After 1983, some virgin females of *T. sinensis* and two strains of the native species *T. beneficus* (Ôtake, 1987) were paired with the males of those different species and/or strains. They were confined in a small glass tube with drops of honey for at least two days for mating. Then the females were released into a nylon-mesh bag that was placed over a branch of the Japanese chestnut tree on which galls were formed (i.e., the bagging method of Ôtake *et al*., 1984). The next spring, the emergence of the offspring was observed in the same manner as described earlier. Some of the female offspring were backcrossed to the males of the parent species, and the emergence of progeny was also recorded the next spring.

RESULTS AND DISCUSSION

Indigenous Parasitoids of *Dryocosmus kuriphilus* in Ibaraki Prefecture

Emergence of adult parasitoids is summarized in Table 1. Before the initial introduction of *T. sinensis*, 10 species of hymenopterous parasitoids were discovered at the release site (NIFTS). Since the percentage of parasitism was not high for any of the parasitoids, it is unlikely that the indigenous parasitoids effectively controlled the chestnut gall wasp population in the southern part of Ibaraki Prefecture.

Table 1. Parasitoids recorded from the galls of *Dryocosmus kuriphilus*Yasumatsu in Ibaraki Prefecture, Japan, before introduction of *Torymus sinensis* Kamijo from China.

Parasitoids	1978	1979	1980	1981
Torymus beneficus Yasumatsu et Kamijo (Torymidae)	-[a]	E[b]	E	E
Torymus geranii Walker (Torymidae)	E	E	E	E
Megastigmus nipponicus Yasumatsu et Kamijo (Torymidae)	N[c]	E	N	N
Ormyrus punctiger Westwood (Ormyridae)	E	N	N	N
Ormyrus flavitibialis Yasumatsu et Kamijo (Ormyridae)	E	E	E	E
Eurytoma brunniventris Ratzeburg (Eurytomidae)	E	E	E	E
Eurytoma setigera Mayr (Eurytomidae)	N	N	N	E
Eupelmus urozonus Dalman (Eupelmidae) (male)[d]	E	N	N	E
Eupelmus sp. (Eupelmidae) (male)	N	N	N	E
Eupelmus spp. (Eupelmidae) (female)[d]	E	E	E	E
Pteromalus apantelophagus Crawford (Pteromalidae)	N	N	N	E

[a] No observation,
[b] E=Emerged,
[c] N=Not emerged.
[d] Females of the two *Eupelmus* are morphologically indistinguishable from each other (see, Ôtake et al., 1982).

Establishment and Growth of the *Torymus sinensis* Population at the Release Site

As pointed out by Ôtake *et al*. (1984) and Ôtake (1987), the males of *T. sinensis* are morphologically indistinguishable from those of *T. beneficus*. Therefore, records used to distinguish between these species are for females only. In March 1983, 16,027 withered galls were collected at release sites and adjacent areas. Since 502 females of *T. sinensis* emerged from those galls, the parasitoid was confirmed to have become established at the release site (NIFTS). It is obvious that the *T. sinensis* population increased soon after its establishment. By 1989, the number of *T. sinensis* females emerging per 100 galls was 25 times larger than the number in 1983 (Fig. 1). Since 1989, *T. sinensis* has become completely dominant among the parasitoids of the chestnut gall wasp at the release site (NIFTS) (Piao and Moriya, 1999).

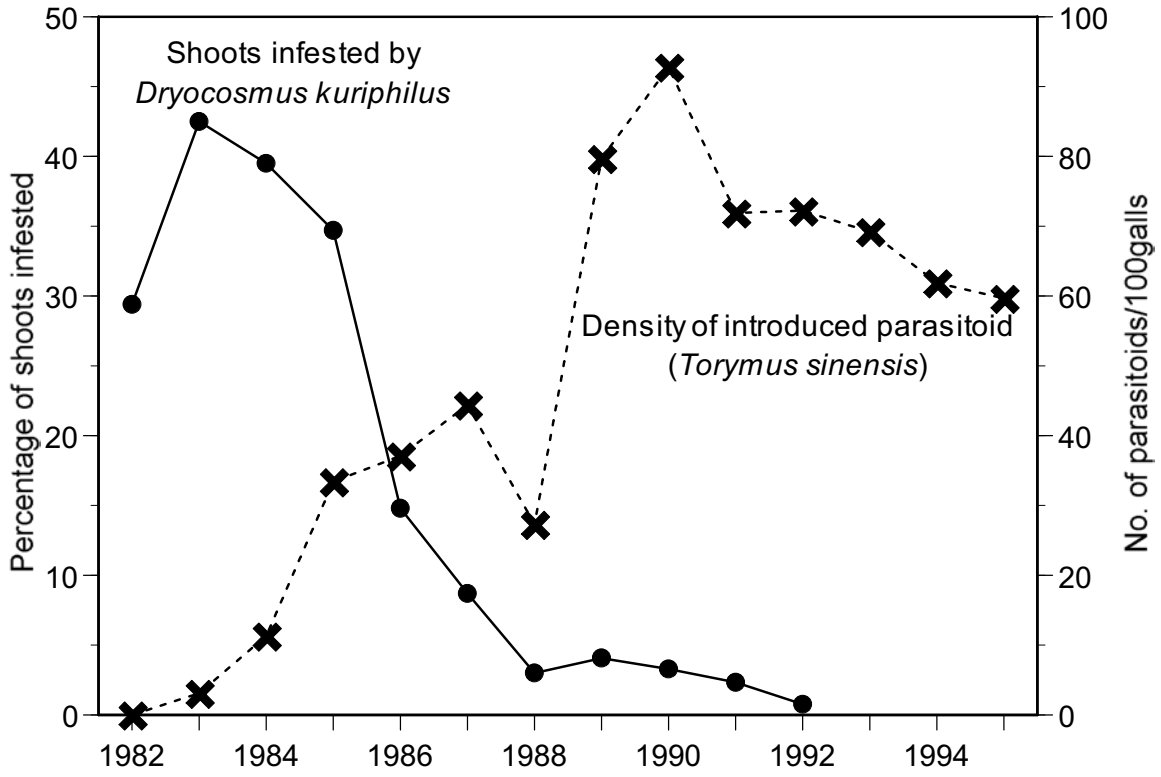

Figure 1. Changes in the percentage of current shoots of chestnut trees infested with *Dryocosmus kuriphilus* Yasumatsu and the emergence of *Torymus sinensis* Kamijo from the withered galls after its release at the National Institute of Fruit Tree Science. Source: Moriya *et al*. (1989a).

Spread of *Torymus sinensis*

Torymus sinensis expanded its geographical range soon after its release (Fig. 2). During the first few years the parasitoid spread gradually, at a rate of less than 1 km/year, followed by more rapid and accelerated spread in the next few years. In the spring of 1989, *T. sinensis* was detected in an area more

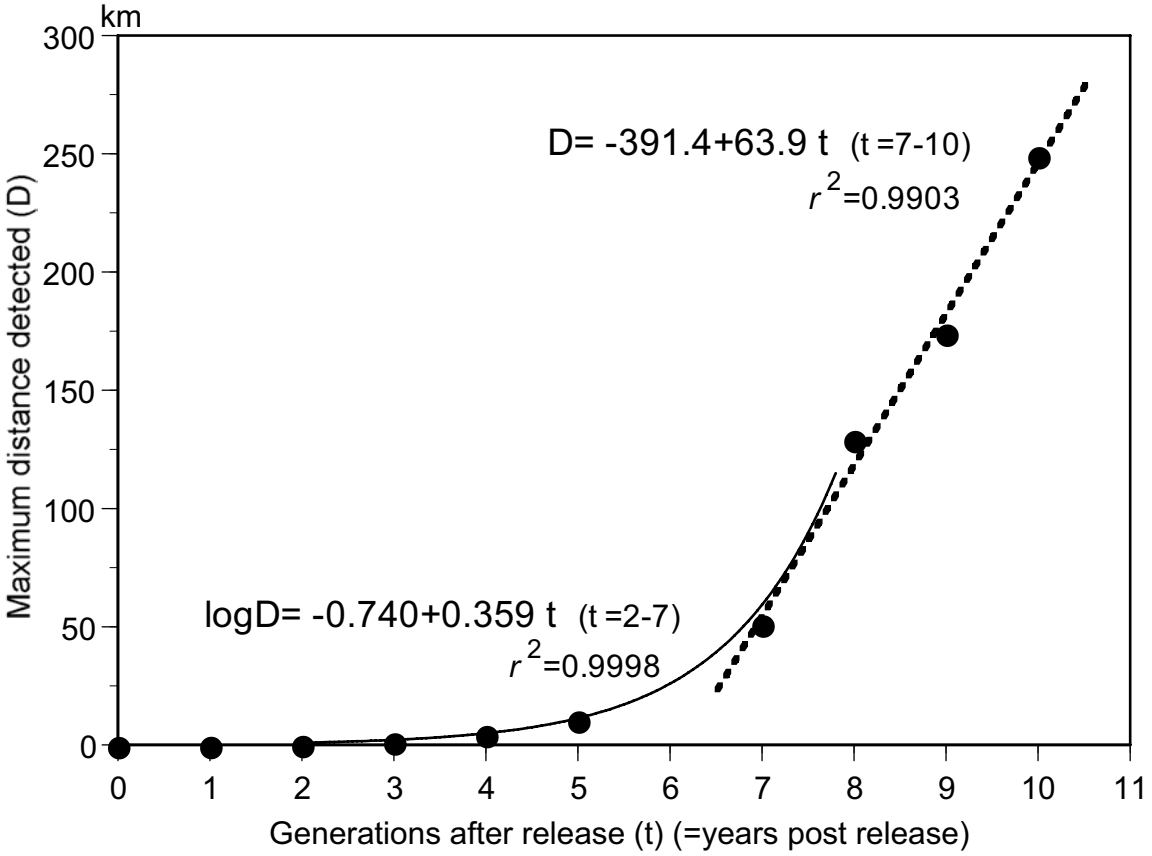

Figure 2. Range expansion of *Torymus sinensis* Kamijo. Relationship between the number of generations (*t*) after release of the wasp at Tsukuba in 1982 and the maximum distance (*D*) from Tsukuba to the locality where *T. sinensis* was detected. Source: Moriya *et al*. (1989b), Shiga (1996, 1997).

than 12 km from the release site (NIFTS). Since then, a steady expansion has been observed at a constant rate of ca 60 km per year (=generation). Consequently, the parasitoids seem to have dispersed, by themselves, several hundred kilometers from the point of release.

Evaluation of *Torymus sinensis* as a Biological Control Agent

The infestation rate of the chestnut gall wasp steadily decreased, from ca 43% shortly after the release to ca 3% in 1988 and less than 1% in 1992 (Fig. 1). According to a 5-year observation from 1960 through 1964 (before the introduction of *T. sinensis*), the estimated chestnut gall wasp population density fluctuated approximately fourfold (Miyashita *et al*., 1965). It is believed, therefore, that the rapid decrease and stable low level of the infestation rate observed at the release site (NIFTS) was due principally to the parasitoid.

The tolerable injury level by the chestnut gall wasp for chestnut trees is considered to be 30% infestation of current shoots (Gyoutoku and Uemura, 1985). This means that the infestation level at the release site became much lower than the tolerable injury level after 1986.

Table 2. Results of the experimental crossing among *Torymus sinensis* Kamijo (Ts), early-season (TbE) and late-season (TbL) strains of *T. beneficus* Yasumatsu et Kamijo, and their hybrids by using the bagging method.

Cross-combination	Year(s)	No. of females released	No. of offspring	
			Males	Females
Reciprocal Cross				
Female × Male				
TbL × Ts	1984-1992	283	152	150
Ts × TbL	1984-1992	283	640	143
TbE × Ts	1990-1992	111	46	33
Ts × TbE	1991-1992	136	208	1
TbE × TbL	1992	31	8	0
TbL × TbE	1992	60	35	2
Backcross				
[F1 female] × Male				
[(TbL)F × (Ts)M] × TbL	1988-1992	48	80	44
[(TbL)F × (Ts)M] × Ts	1988-1991	24	34	52
[(Ts)F × (TbL)M] × TbL	1988,1990-91	40	22	33
[(Ts)F × (TbL)M] × Ts	1988,1990-91	26	87	83

Source: Moriya et al. (1992)

Interaction between *Torymus sinensis* and *T. beneficus*

The results of the experimental crossing among the torymid species/strains are summarized in Table 2. The sex of torymids is simply determined by a haploid-diploid system. Therefore, female offspring are the true hybrids derived from the crossing. When *T. sinensis* was artificially crossed with *T. beneficus*, morphologically intermediate, fertile females were observed among the offspring. Table 2 shows that the hybrid females could be obtained from all of the combinations tested except for *TbE female* x *TbL male*. Although the sex ratio of the offspring varied among the combinations, it seems that the ratio of female offspring was high when the male parent was *T. sinensis*. It should be noted that crossing between *T. sinensis* and *T. beneficus* was confirmed to occur under natural conditions by analyzing the genotype of the malic enzyme (Izawa et al., 1996; Toda et al., 2000; Yara et al., 2000).

There was no evidence for direct competition between *T. sinensis* and *T. beneficus* in the field. However, the reproductive ability of *T. sinensis*, as indicated by the number of eggs deposited (Piao and Moriya, 1992a, b), was higher than that of *T. beneficus*. This might be responsible for the decrease in the number of *T. beneficus* in the chestnut groves at the release site (NIFTS) after the introduction of *T. sinensis*.

The relationship between the two torymids became more and more complicated because a "native" *T. sinensis* was found in Tsushima Island in 1989 (Ohkubo, 1992), Oki Island in 1994 (Toda *et al*., 2000), and Akitsu, Hiroshima Prefecture, in 1992, before the introduction and/or expansion of the imported *T. sinensis* population. Furthermore, a different strain of *T. sinensis* has been found in South Korea (Murakami *et al*., 1995). Presently, little information is available on the origins of those populations. Now, the introduction of *T. sinensis* is widely known as one of the typical successful cases of classical biological control in Japan (Murakami, 1997), but the basic research should be continued.

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REFERENCES

Gyoutoku, Y. and M. Uemura. 1985. Ecology and biological control of the chestnut gall wasp, *Dryocosmus kuriphilus* Yasumatsu (Hymenoptera: Cynipidae). 1. Damage and parasitization in Kumamoto Prefecture. *Proceedings of the Association for Plant Protection of Kyushu* 31: 213-215 (in Japanese).

Izawa, H., Mh. Osakabe, S. Moriya, and S. Toda. 1996. Use of malic enzyme to detect hybrids between *Torymus sinensis* and *T. beneficus* (Hymenoptera: Torymidae) attacking *Dryocosmus kuriphilus* (Hymenoptera: Cynipidae) and possibility of natural hybridization. *Japanese Journal of Applied Entomology and Zoology* 40: 205-208 (in Japanese with English summary).

Kajiura, M. and Y. Machida. 1961. The breeding of resistant varieties to some insects and diseases in fruit trees. *Japanese Journal of Breeding* 11: 137-140 (in Japanese).

Kamijo, K. 1982. Two new species of *Torymus* (Hymenoptera, Torymidae) reared from *Dryocosmus kuriphilus* (Hymenoptera, Cynipidae) in China and Korea. *Kontyû, Tokyo* 50: 505-510.

Miyashita K., Y. Itô, K. Nakamura, M. Nakamura, and M. Kondo. 1965. Population dynamics of the chestnut gall-wasp, *Dryocosmus kuriphilus* Yasumatsu (Hymenoptera: Cynipidae). III. Five year observations on population fluctuations. *Japanese Journal of Applied Entomology and Zoology* 9: 42-52.

Moriya, S., K. Inoue, A. Ôtake, M. Shiga, and M. Mabuchi. 1989a. Decline of the chestnut gall wasp population, *Dryocosmus kuriphilus* Yasumatsu (Hymenoptera: Cynipidae) after the establishment of *Torymus sinensis* Kamijo (Hymenoptera: Torymidae). *Applied Entomology and Zoology* 24: 231-233.

Moriya, S., K. Inoue, and M. Mabuchi. 1989b. The use of *Torymus sinensis* to control chestnut gall wasp, *Dryocosmus kuriphilus*, in Japan. *Food and Fertilizer Technology Center (FFTC) Technical Bulletin* 118: 1-12.

Moriya, S., K. Inoue, M. Shiga, and M. Mabuchi. 1992. Interspecific relationship between an introduced parasitoid, *Torymus sinensis* Kamijo, as a biological control agent of the chestnut gall wasp, *Dryocosmus kuriphilus* Yasumatsu, and an endemic parasitoid, *T. beneficus* Yasumatsu et Kamijo. *Acta Phytopathologica et Entomologica Hungarica* 27: 479-483.

Murakami, Y. 1980. Recent topics on the chestnut gall wasp, with special reference to a report from China. *Nogyô oyobi Engei (Agriculture and Horticulture)* 55: 249-253 (in Japanese).

Murakami, Y. 1997. *Natural Enemies of the Chestnut Gall Wasp: Approaches to Biological Control.* Kyushu University Press, Fukuoka, Japan. (in Japanese).

Murakami, Y., K. Umeya, and N. Oho. 1977. A preliminary introduction and release of a parasitoid (Chalcidoidea, Torymidae) of the chestnut gall wasp, *Dryocosmus kuriphilus* Yasumatsu (Cynipidae) from China. *Japanese Journal of Applied Entomology and Zoology* 21: 197-203 (in Japanese with English summary).

Murakami, Y., H.-B. Ao, and C.-H. Chiang. 1980. Natural enemies in the chestnut gall wasp in Hopei Province, China (Hymenoptera: Chalcidoidea). *Applied Entomology and Zoology* 15: 184-186.

Murakami, Y., N. Ohkubo, S. Moriya, Y. Gyoutoku, C.-H. Kim, and J.-K. Kim. 1995. Parasitoids of *Dryocosmus kuriphilus* (Hymenoptera: Cynipidae) in South Korea with particular reference to ecologically different types of *Torymus* (*Syntomaspis*) *sinensis* (Hymenoptera: Torymidae). *Applied Entomology and Zoology* 30: 277-284.

Ohkubo, N. 1992. Distribution of parasitoids of chestnut gall wasp, *Dryocosmus kuriphilus* Yasumatsu in Nagasaki Prefecture. *Proceedings of the Association for Plant Protection of Kyushu* 38: 190-192 (in Japanese).

Oho, N. and I. Shimura. 1970. Research process on the chestnut gall wasp and some recent problems about its damage. *Shokubutsu Boeki (Plant Protection)* 24: 421-427 (in Japanese).

Oho, N. and K. Umeya. 1975. Chestnut gall wasp is found in the People's Republic of China. *Shokubutsu Boeki (Plant Protection)* 29: 463-464 (in Japanese).

Ôtake, A. 1980. Chestnut gall wasp, *Dryocosmus kuriphilus* Yasumatsu (Hymenoptera: Cynipidae): a preliminary study on trend of adult emergence and some other ecological aspects related to the final stage of its life cycle. *Applied Entomology and Zoology* 15: 96-105.

Ôtake, A. 1987. Comparison of some morphological characters among two strains of *Torymus beneficus* Yasumatsu et Kamijo and *T. sinensis* Kamijo (Hymenoptera: Torymidae). *Applied Entomology and Zoology* 22: 600-609.

Ôtake, A. 1989. Chestnut gall wasp, *Dryocosmus kuriphilus* Yasumatsu (Hymenoptera: Cynipidae): analysis of records on cell contents inside galls and emergence of wasps and parasitoids outside galls. *Applied Entomology and Zoology* 24: 193-201.

Ôtake, A., M. Shiga, and S. Moriya. 1982. A study on parasitism of the chestnut gall wasp, *Dryocosmus kuriphilus* Yasumatsu (Hymenoptera: Cynipidae) by parasitoids indigenous to Japan. *Bulletin of the Fruit Tree Research Station* A9: 177-192.

Ôtake, A., S. Moriya, and M. Shiga. 1984. Colonization of *Torymus sinensis* Kamijo (Hymenoptera: Torymidae), a parasitoid of the chestnut gall wasp, *Dryocosmus kuriphilus* Yasumatsu (Hymenoptera: Cynipidae), introduced from China. *Applied Entomology and Zoology* 19: 111-114.

Piao, C.-S. and S. Moriya. 1992a. Ovarian and egg development of *Torymus sinensis* Kamijo and ovarian development of two strains of *T. beneficus* Yasumatsu et Kamijo (Hymenoptera: Torymidae). *Bulletin of the Fruit Tree Research Station* 22: 79-89 (in Japanese with English summary).

Piao, C.-S. and S. Moriya. 1992b. Longevity and oviposition of *Torymus sinensis* Kamijo and two strains of *T. beneficus* Yasumatsu et Kamijo (Hymenoptera: Torymidae). *Japanese Journal of Applied Entomology and Zoology* 36: 113-118 (in Japanese with English summary).

Piao, C.-S. and S. Moriya. 1999. Oviposition of *Torymus sinensis* Kamijo (Hymenoptera: Torymidae) under natural conditions. *Entomological Science* 2: 329-334.

Shiga, M. 1996. Management of exotic insect pests in Japan, pp. 3-19. *In* Hokyo, N. and G. Norton (eds.). *Proceedings of the International Workshop on Pest Management Strategies in Asian Monsoon Agroecosystems (Kumamoto, 1995).* Kyushu National Agricultural Experiment Station, Kumamoto, Japan.

Shiga, M. 1997. Classical biological control of the chestnut gall wasp, *Dryocosmus kuriphilus*: present status and interactions between an introduced parasitoid, *Torymus sinensis*, and native parasitoids, pp. 175-188. *In* Yano, E., K. Matsuo, M. Shiyomi, and D. A. Andow (eds.). *Biological Invasions of Ecosystem by Pests and Beneficial Organisms*. National Institute of Agro-Environmental Sciences, Tsukuba, Japan.

Shimura, I. 1972. Studies on the breeding of chestnut, *Castanea* spp. II. Parasitic variation in the chestnut gall wasp, *Dryocosmus kuriphilus* Yasumatsu. *Bulletin of the Horticultural Research Station* A11: 1-13 (in Japanese with English summary).

Shimura, I. 1973. Studies on the breeding behaviors of several characters in chestnut, *Castanea* spp. III. Damages variation in the chestnut cultivars by the chestnut gall wasp, *Dryocosmus kuriphilus* Yasumatsu. *Japanese Journal of Breeding* 23: 311-319 (in Japanese with English summary).

Shiraga, T. 1951. Problems and control of the chestnut gall wasp. *Nogyô oyobi Engei (Agriculture and Horticulture)* 26: 167-170 (in Japanese).

Tamura, M. 1960. Studies on the chestnut gall wasp, *Dryocosmus kuriphilus* Yasumatsu (Part 2). On the life history. *Journal of Agricultural Sciences, Tokyo Nogyo Daigaku* 6: 13-26 (in Japanese with English summary).

Toda, S., M. Miyazaki, Mh. Osakabe, and S. Komazaki. 2000. Occurrence and hybridization of two parasitoid wasps, *Torymus sinensis* Kamijo and *T. beneficus* Yasumatsu et Kamijo (Hymenoptera: Torymidae), in the Oki Islands. *Applied Entomology and Zoology* 35: 151-154.

Yara, K., E. Yano, T. Sasawaki, and M. Shiga. 2000. Detection of hybrids between introduced *Torymus sinensis* and native *T. beneficus* (Hymenoptera: Torymidae) in central Japan, using malic enzyme. *Applied Entomology and Zoology* 35: 201-206.

Yasumatsu, K. 1951. A new *Dryocosmus* injurious to chestnut trees in Japan (Hym., Cynipidae). *Mushi* 22: 89-93.