A review of the status of the larval parasitoid, *Asecodes hispinarum* Boucek, and of the pupal parasitoid, *Tetrastichus brontispae* Ferriere (Hymenoptera: Eulophidae), as biological control agents of the coconut leaf beetle, *Brontispa longissima* (Gestro) (Coleoptera: Chrysomelidae: Cassidinae), in the Asia-Pacific Region¹

He Liansheng², Zuria Mohama Din² and Yap Mei Lai²

Key Words: *Asecodes hispinarum*, *Tetrastichus brontispae*, Hymenoptera, Eulophidae, biological control, *Brontispa longissima*, Coleoptera, Chrysomelidae

Abstract: The Coconut Leaf Beetle, *Brontispa longissima*, endemic to Indonesia and Papua New Guinea, has spread to many countries in Asia and the Pacific region, where it has become a serious pest. Several countries have achieved significant control of *B. longissima* by releasing and establishing parasitoids, such as *Asecodes hispinarum* and *Tetrastichus brontispae*, which attack immature stages of the pest. A review of previous works undertaken on the biological control of the Coconut Leaf Beetle in these countries and elsewhere indicate that a combined release of *A. hispinarum*, with *T. brontispae* is an excellent tool to control *B. longissima*. Biological control of *B. longissima* is also seen to be environmentally sound and cost effective.

Introduction

The Coconut Leaf Beetle, *Brontispa longissima* (Gestro) (Coleoptera: Chrysomelidae: Cassidinae: Hispines: Tribe Cryptonychini Chapuis: *Brontispa* Sharp) (Staines, 2012) is one of the most damaging pests of coconut, *Cocos nucifera* L. This species, which has been reported on several species of palms (Arecaceae) (Staines, 2012), is also known as the Two-coloured Coconut Leaf Beetle or the Coconut Hispine Beetle. The larvae and adults feed on the tissues of developing and unopened leaves of palm trees. This hispid beetle can cause significant production loss, and high infestation may result in the death of the trees (Kalshoven, 1981; Liebrechts and Chapman, 2004). Damage to palms is followed by substantial yield loss. A study by the Food and Agriculture Organization (FAO) of the United Nations showed that, if left uncontrolled, the damage would be in excess of US\$40 million annually in Vietnam alone (Liebrechts and Chapman, 2004).

Brontispa longissima is believed to be endemic to Indonesia, Papua New Guinea and possibly also to Malaysia (FAO, 1981; Liebrechts and Chapman,

¹ Submitted on July 4, 2013. Accepted on July 15, 2014. Last revisions received on May 12, 2014.

² Plant Health Laboratory Department, Laboratories Group, Agri-Food and Veterinary Authority of Singapore, Singapore 718827. E-mails: HE_Lian_Sheng@ava.gov.sg, Zuria_Mohana_Din@AVA.GOV.SG, YAP_Mei_Lai@ava.gov.sg, respectively.

2004). In recent years, the species has become widespread in South East Asia and the Pacific region. Outside its presumed native range, it was first detected in the Mekong Delta in Vietnam in the late 1990's (Liebregts and Chapman, 2004). The geographical distribution of *B. longissima* is illustrated in Rethinam and Singh (2007), Nakamura et al. (2012), and CABI (2014). Two mitochondrial clades of *B. longissima*, each with different life history traits, are discussed in Nakamura et al. (2012, see also references therein for more details).

Chemical control of this pest has been extensively studied. Several insecticides including imidacloprid, chlorfenvinfos, diazinon, and carbofuran were used to combat the Coconut Leaf Beetle (Baringbing and Karmawati, 1992; He et al., 2006). However, the effects of those treatments last only from several days to several weeks depending on the property of pesticides and the methods of application. In addition, chemical control substantially increased costs and threatened the ecosystem. Until 2004, this invasive pest did not have adequate natural enemies to suppress its populations in Southern East Asia. Historically, biological control has been used primarily on exotic pests (Grandgirard et al., 2008; Hall et al., 1980; Hall and Ehler, 1979). Hence, the biological control of *B. longissima* was considered a good approach to tackle this pest.

Biological control as a pest control measure

Biological control is an effective control method for pestiferous insects, mites, weeds and plant diseases, using other living organisms (Flint and Dreistadt, 1998). A compelling motivation for adoption of biological control is the reduced ongoing expenditure for pesticides, labour, specialized equipment and potentially a permanent return to ecological conditions (Norgaard, 1988, Pickett et al., 1996; Jetter et al., 1997). Biological control of arthropod pests becomes an important component of cost effective, environmentally benign integrated pest management (Gurr et al., 2000).

Based on the biological control agents used, there are broad sense biological controls and classic biological controls. In the broad sense, biological control is any action of one organism against another. This approach to biological control embraces the use of natural 'macrobial' and 'microbial' agents (Huffaker, 1977, van Lenteren et al., 2006a). Many biological control schemes use predatory insects and mites, insects that parasitize other insects (parasitoids) or nematodes, targeted against insect and mite pests; these are the so-called 'macrobial' agents. There are also various 'microbial' agents (bacteria, viruses and fungi) that have been developed and applied for arthropod biological control programs (van Lenteren and Woets, 1988; van Lenteren, 2003; van Lenteren et al., 2006a, 2006b). In its narrow sense, biological control has meant a planned introduction of a biological agent that may reduce a pest problem (Huffaker, 1977).

Narrow sense biological control has been applied to combat insect pests for more than hundred years, and includes classical biological control (CBC) and

augmentative biological control (ABC) (van Lenteren, 2000, 2003; van Lenteren et al., 2006a). Classical biological control of insects, in which exotic natural enemies are introduced to control exotic pests, has been applied for more than 120 years and the release of more than 2,000 species of natural enemies have resulted in the permanent reduction of at least 165 pest species worldwide (Greathead, 1995; Gurr and Wratten, 2000). In contrast, augmentative biological control, in which exotic or native natural enemies are periodically released, has been used for close to 90 – 100 years with more than 150 species of natural enemies available on demand for the control of about 100 pest species (van Lenteren, 2003).

Contrary to the thorough environmental risk evaluations applied in the search for natural enemies of weeds (Blossey, 1995; Lonsdale et al. 2001, Wapshere, 1974), potential risks of biological control agents for arthropod control has not been routinely studied in pre-release evaluations (van Lenteren and Woets, 1988; van Lenteren et al., 2003), with the exception of several CBC programmes for which accurate non-target species testing has been used (Barratt et al., 1999; Neuenschwander and Markham, 2001). Until now, very few problems have been reported concerning negative effects of release of arthropods for the control of pestiferous arthropods (Lynch et al., 2001), despite more than 5,000 introductions in at least 196 countries or islands (Greathead, 1995, Gurr and Wratten, 2000; van Lenteren, 2000, 2003). This suggests the safety of biological control approaches. However, insect pest management with biological control is undergoing dramatic change due to heightened awareness of non-target impacts and increasing scrutiny by regulatory agencies.

Discussions on the risk of release of exotic natural enemies for non-target species took a prominent place in biological control programs. Retrospective analyses of biological control projects have provided quantitative data on non-target effects and illustrated the need for risk assessments to increase the future safety of biological control (Louda et al., 2003, Lynch et al., 2001). In this review, the terminologies related to biological control and environmental risk assessments (ERA) have been taken from recent publications in this area [Convention on Biological Diversity (CBD), 2002; Eilenberg et al., 2001; International Plant Protection Convention (IPPC), 2005; van Lenteren, 2006)]. Thus far, very few negative reports of pest risk analysis (PRA) or ERA are found for either CBC or ABC (Greathead, 1995; Gurr and Wratten, 2000; van Lenteren, 2000, 2003).

In the past several years, classic biological control of *B. longissima* by introducing exotic wasps was extensively studied and widely adopted (Wood, 2002; CFC/DFID/APCC/FAO, 2004; Chen et al., 2010; Liebrechts et al. 2006; Liu et al. 2008; Lu et al. 2005a, 2005b, 2006; Sun et al., 2011; Tang et al., 2006, 2007a, 2007b; Pundee, 2009; Xu et al., 2008). A literature review was carried out to better understand how to control the coconut hispid using parasitoid wasps in South East Asia. The foci of the search were parasitoid wasps in the

family Eulophidae that attack the larval or pupal stages of *B. longissima*. This search included the larval parasitoid *Asecodes hispinarum* and the pupal parasitoid *Tetrastichus brontispae*.

Biological control of *B. longissima*

Biological control by using parasitoids, predators and entomopathogenic fungi has been shown to reduce the field population of *B. longissima* (Meldy et al., 2004). Natural enemies that attack only during one stage of the pest may not achieve satisfactory control of *B. longissima*; observations from South Sulawesi showed that the pest had overlapping generations (Meldy et al., 2004).

The parasitoid complex of *B. longissima* comprised parasitoids of eggs, larvae and pupae (Hollingsworth et al., 1988). The common egg parasitic wasps were *Haekeliana brontispa* Ferriere, *Trichogrammatoidea nana* Zehntner (both Hymenoptera: Trichogrammatidae) and species of *Ooencyrtus* (Hymenoptera: Encyrtidae). The parasitoid of the larvae, *A. hispinarum*, and parasitoid of pupae, *T. brontispae*, were reported to be common and effective (Lever, 1969). After scrupulous screening, those two parasitoids were selected as biocontrol agents to combat *B. longissima* by FAO (FAO, 2004).

To facilitate the biological control of coconut hispid, FAO conducted a Technical Cooperation Programme (TCP) during 2003-2005 in Vietnam, Nauru (located in the Pacific Ocean), and Maldives (located in the Indian Ocean). Under this project, collection of the parasitoid *A. hispinarum* from Samoa and its subsequent introduction in these countries was conducted. Initial surveys confirmed the establishment of the parasitoid in Vietnam and Maldives, where observations showed that damage to young emerging leaves was reduced. The Vietnam project showed a return on investment of US\$3,000 for every dollar invested by FAO (FAO, 2004). Since then, successful control of *B. longissima* with high cost/benefit ratios has been achieved in several other countries by importing and establishing the two parasitoids that attack immature stages of the Coconut Leaf Beetle. The successful locations included Celebes (Indonesia), Tahiti, Solomon Islands, Western Samoa (Volgele, 1989), Taiwan (Chiu and Chen, 1985), Vietnam (Viet, 2004) and China (Li et al., 2008). Many other countries, including Thailand and Maldives, are actively mass rearing and releasing the two species of parasitic wasps against *B. longissima* (FAO, 2004; Fu and Xiong, 2004; Htwe et al., 2013; Pundee et al., 2009; Shafia, 2004; Sindhusake and Amporn, 2004).

Characteristic attributes of *A. hispinarum* and *T. brontispae* relevant to the success or failure of biological control

Understanding the characteristic attributes of biological control agents is very important to the success or failure of releases. Through retrospective analysis, it is clear that there are situations where arthropod biological control agents have been successful and other situations where they have failed to

impact the target pest species. In other situations, biological control agents have backfired, causing more harm than good (Greathead, 1986; Hunt et al., 2008). Studying the attributes associated with effective biological pest control and high environmental adaptability of the biocontrol agents would help in selecting potentially successful biological control projects (Berkvens et al., 2009; Haye et al., 2009; Murray et al., 2009).

Murdoch (1994) summarized a principle hypothesized to govern the effectiveness of specialized biological control agents. Agents that can persist when their prey items or host populations are very low in number should be favoured, assuming other traits equal. In addition, a number of authors have analyzed the historical record of biological control agents to identify factors or traits that are associated with success and failure (Hawkins et al., 1993; Hawkins and Cornell, 1994). Table 1 below highlights the successful attributes of some biological agents.

Table 1. Attributes that contributed to the success of biological control.

Target pest species	Biological agent used	Attributes
<i>Icerya purchasi</i> Maskell	<i>Rodolia cardinalis</i> (Mulsant)	<ul style="list-style-type: none"> ● Thermal tolerance ● Short development time with respect to prey (DeBach and Quezada, 1973)
<i>Trialeurodes vaporariorum</i> (Westwood)	<i>Encarsia formosa</i> Gahan	<ul style="list-style-type: none"> ● High dispersal ability ● High searching ability ● Accepts all immature host stages ● Ease of mass rearing (van Lenteren, 1995)
<i>Tetranychus urticae</i> Koch	<i>Phytoseiulus persimilis</i> Athias- Henriot	<ul style="list-style-type: none"> ● Voracious feeding ● High dispersal ability ● High searching ability ● Ease of mass rearing ● Availability of pesticide resistant strain (van Lenteren, 1995)
<i>Phenacoccus manihoti</i> Matile-Ferrero	<i>Apoanagyrus lopezi</i> De Santis	<ul style="list-style-type: none"> ● Attack of early host instars ● Production of more females on young hosts ● Superior competitive ability ● High search capacity (Neuenschwander, 2001)

Biology and mass rearing of the larval parasitoid, *A. hispinarum* has been conducted under laboratory conditions by several authors in various countries (Sindhusake and Amporn, 2004; Htwe et al., 2013; Lu et al., 2005a, 2005b,

2008; Sun et al., 2011; Tang et al., 2006, 2007a, 2007b; Pundee, 2009; and Viet, 2004). In 2006, the mass rearing of both species of wasp was initiated in the Entomology and Nematology laboratory, Plant Health Laboratory Department, Agri-Food and Veterinary Authority of Singapore (AVA). Laboratory populations of these two species were established and mass rearing protocols developed (AVA, 2011, unpublished report). The characteristics of these two species were found to be similar to those reported under laboratory conditions. Attributes of *T. brontispae* and *A. hispinarum* relevant to success or failure of releases for pest biological control are summarised in Table 2.

Qian et al. (2011) released *A. hispinarum* and *T. brontispae* simultaneously in the same locations to control *B. longissima*. The results indicated that *B. longissima* was most effectively controlled when there were 40 - 60 *A. hispinarum* and 10 - 20 *T. brontispae* in each container (the ratio of *T. brontispae* to *A. hispinarum* was approximately one to four).

Table 2. Characteristic attributes of *T. brontispae* and *A. hispinarum* relevant to the success or failure of biological control.

Important attributes	<i>Asecodes hispinarum</i>	<i>Tetrastichus brontispae</i>
Response to temperature	<ul style="list-style-type: none">● At 22 °C, <i>A. hispinarum</i> adults' survival was the longest (Lu et al., 2005a, 2005b; Tang et al., 2007a, 2007b and Pundee, 2009).● The effective temperature range was from 16 - 32 °C (Tang et al., 2007a).● The highest parasitic efficiency was at 28 °C (Tang et al., 2007a).● Temperature had no effect on the sex ratio of the parasitoid offspring (Lu, 2008).	<ul style="list-style-type: none">● Optimum temperature at 20 - 28 °C with parasitic ratio reached 95% (Chen et al., 2010).● When temperature was below 18°C, parasitic ratio was 52.2% and when above 30 °C, it was 69.5% (Chen et al., 2010).
Adult longevity	<ul style="list-style-type: none">● When fed with 10% honey (v/v), the average longevity of the wasp was 4.9 days (Pundee, 2009).● The longest mean developmental time was 23.8 days while the shortest was 16.5 day at 28 °C (Htwe et al., 2013).	<ul style="list-style-type: none">● When fed with 10% honey (v/v), the longevity of the wasp was 13.4 days (Huang et al., 2007).

Fecundity	<ul style="list-style-type: none"> ● 43 eggs/female (Lu et al., 2005a) to 47.3 eggs / female (Pundee, 2009). 	<ul style="list-style-type: none"> ● 53.6 eggs/female (Huang et al., 2007).
Host range	<ul style="list-style-type: none"> ● The larvae of <i>Plesispa reichei</i> and <i>B. longissima</i> but the latter was preferred (Sindhusake and Amporn, 2004; Pundee, 2009). ● The 3rd and 4th instars larvae of <i>B. longissima</i> were the best host stages for mass production (Htwe et al., 2013; Pundee, 2009; Viet, 2004). 	<ul style="list-style-type: none"> ● Pupae of <i>B. longissima</i> (Ding et al., 2007). ● Females of <i>T. brontispae</i> could parasitize pre-pupae and 1 to 5-day-old pupae but 1-day pupae preferred (Chen et al., 2010).
Life cycle	<ul style="list-style-type: none"> ● 16 – 23 days (Htwe et al., 2013). 	<ul style="list-style-type: none"> ● 17.1 – 46.2 days (Chen et al., 2010).
Behaviour	<ul style="list-style-type: none"> ● The hunting time of <i>A. hispinarum</i> was not affected by change of temperature range of 16 °C to 28 °C (Tang et al., 2007a). ● The percentage of parasitized <i>B. longissima</i> larva increased with the increase in host density (Tang et al., 2007b). ● The peak ovi-position was within 12 hours after mating (Lu et al., 2005b). ● The optimal time for parasitisation was at 24 hours after emergence of adults (Pundee, 2009). ● The parasitization efficiency decreased with the increase in <i>A. hispinarum</i> density (Lu et al., 2005b). 	<ul style="list-style-type: none"> ● The parasitized rates on pupae of <i>B. longissima</i> reached at 72% to 92.78% on 45 days after releasing (Ding et al., 2007). ● 6 months after release, <i>B. longissima</i> per tree decreased between 3.3 to 44.3 times the original population size (Ding et al., 2007). ● The dispersal distance was around 10-50 metres 20 days after field release. ● The longest dispersal distance was 6.06 km, seven months after release (Ma et al., 2006b).

***Asecodes hispinarum* as a biological control agent**

Asecodes hispinarum was reported to have originated in Papua New Guinea (Boucek, 1988; Voegelé, 1989). This parasitoid was successfully introduced into

Samoa in the early 1980's for the control of *B. longissima* (Volgele and Zeddies, 1990). *Asecodes hispinarum* was reported to be the only biological control agent that controlled the pest in Western Samoa during the 1980's. In the last thirty years, *A. hispinarum* has played a very important role in the control of the Coconut Leaf Beetle with no negative effects (Volgele and Zeddies, 1990).

In 2003, FAO collected the parasitoid *A. hispinarum* from West Samoa and this parasitoid was identified as the main biological control agent of coconut hispids for their Technical Cooperation Projects (TCP). These were later introduced into southern Vietnam and other Asian countries to control *B. longissima* (FAO, 2004). In Vietnam, these tiny wasps were first reared in containment facilities and released in 15 provinces of south and central Vietnam (Viet, 2004).

Early observations indicated that the effectiveness of the parasitoids was likely to be affected by the prevailing environmental conditions where they were released. In view of this, FAO organized a research group to strengthen the biological control programme, and completed exploratory surveys in Indonesia, Papua New Guinea and the Solomon Islands. Results of field surveys indicated that the parasitoids spread at the rate of 5-8 km in two months and, within four months, 60-90% recovery of palms was observed (FAO, 2004). In Vietnam, it was expected that the damage levels would be reduced to levels similar to those seen in Samoa, where *B. longissima* damaged palms were uncommon after the release of the parasitoids (Viet, 2004).

In the Maldives, the parasitoids established within two months after initial field releases in February 2004. The newly emerging leaves appeared to show less damage, although statistically significant reduction in damage was not observed. This reduction could be attributed to the impact of the parasitoids (Shafia, 2004).

China organized a group of experts to study the biological control of the Coconut Leaf Beetle using *A. hispinarum* in Vietnam (Fu and Xiong, 2004). *Asecodes hispinarum* was subsequently brought to Hainan, China, in March 2004 and after appropriate risk assessment, it was released in Hainan Province, China. To evaluate the potential efficacy of this parasitoid in Hainan, under containment conditions, a series of relevant research was conducted to study the morphology, development, behavior, biological parameters due to temperature, feeding and host range of this species (Table 2). *Asecodes hispinarum* consignment did not bring dangerous microbes and parasites, and the wasps did not parasitize other important native insects, such as ladybird beetles, silkworms, honeybees, and moths (Fu and Xiong, 2004). Therefore, *A. hispinarum* must be a monophagous or oligophagous insect (Sindhusake and Amporn, 2004; Pundee, 2009). No negative impact to the environment, economy or ecology was observed (Fu and Xiong, 2004; Sindhusake and Amporn, 2004; Pundee, 2009) by its release and this corroborates our observations in Singapore (AVA, 2011 unpublished report).

After a safety evaluation, *A. hispinarum* has been released in the north (Haikou), the south (Sanya) and the east (Qionghai) of Hainan, China, since August 2004. A primary survey to study the efficacy of the released natural enemy found that the number of Coconut Leaf Beetles decreased greatly, the infested trees recovered to a certain degree, and the parasitisation rate was 10-40% (Fu and Xiong, 2004). The effects of different larval instars of the beetle on parasitism, and the influences of temperature and humidity on development of *A. Hispinarum*, were also investigated. Under laboratory conditions ($24^{\circ}\text{C} \pm 2^{\circ}\text{C}$ and $\text{RH } 75\% \pm 10\%$), the mean developmental duration of egg, larva and pupa were 2.8 days, 6.7 days and 7.5 days, respectively; the longevity of adults without nutritional supplements was 2.5 days on average. Both the temperature and nutritional supplement affected the longevity of adults, and the mean longevity of adult females was longer than that of adult males. Fecundity (per female) was 43 on average and the peak of oviposition occurred within 12 hours after mating. The functional response of *A. hispinarum* to 4th instar larvae of *B. longissima* belonged to Holling's type II and the parasitisation efficiency of *A. hispinarum* decreased with increase in *A. hispinarum* density (Fu and Xiong, 2004; Lu et al., 2005).

Biological control in Vietnam showed huge benefits in the cost-benefit analysis. By mid 2002, around 9.4 million trees were infested by *B. longissima* and until mid 2004, the pest infestation had caused 30% loss in fruit production, death of 5% of trees (at an estimated cost of US\$23.8 million) and had also damaged 13,000 ornamental palms at an estimated cost of US\$838,000 (FAO, 2004; Viet, 2004). The cost of pesticide applications amounted to approximately US\$715,000, which was borne by the federal and provincial governments. This cost did not include the labour undertaken by the farmer volunteers involved in the control programme. Overall, the cost of FAO -TCP (US\$350,000) was very small when compared to the losses caused by *B. longissima*. Using a unit price of US\$0.10 per coconut (including husk), a tentative analysis of various economical data points was conducted, predicting returns of one billion dollars over a 30-year period or returns of US\$2,000-3,000 for every dollar invested in the project (Viet, 2004). Apart from Vietnam, China, Maldives and Nauru (located in the Pacific Ocean), *A. hispinarum* was also found to be successful controlling *B. longissima* in Thailand, Cambodia, Laos, and Indonesia (Boucek, 1988; Shafia, 2004; Sindhusake and Winothai, 2004; Viet, 2004; Volgele, 1989).

In addition to the reports from China (Fu and Xiong, 2004), researchers in Thailand and Vietnam also did not encounter *A. hispinarum* parasitizing larvae of darkling beetles, *Tenebrio molitor* Linnaeus (Coleoptera: Tenebrionidae); lady bird beetles, *Hippodamia convergens* Guérin-Méneville (Coleoptera: Coccinellidae); the common cutworm, *Spodoptera litura* (Fabricius) (Lepidoptera: Noctuidae); or lacewings, *Mallada basalis* (Walker), *Chrysoperla carnea* (Stephens) (the latter two Neuroptera: Chrysopidae) (Sindhusake and

Winothai, 2004; Viet, 2004). Results of host range studies further confirmed that *A. hispinarum* was a monophagous or oligophagous parasitoid (Sindhusake and Winothai, 2004). The wasps would automatically disappear once their hosts vanished. Therefore, *A. hispinarum* is considered quite safe to non-target insects as well as plants.

***Tetrastichus brontispae* as a biological control agent**

Ferriere (1933), considered *Tetrastichus brontispae* a main natural enemy of *B. Longissima*, as it parasitizes the larval and pupal stages. *Tetrastichus brontispae* was found to be native to Java, Indonesia (Kalshoven, 1981; Lever 1969; Meldy et al., 2004; Tjoa, 1953). Studies on the use of *T. brontispae* as a pupal parasitoid have been carried out by many researchers (Kalshoven, 1981; Lever, 1969; Tjoa, 1953, 1965). There is a long history in the use of the wasp, *T. brontispae*, as a biocontrol agent. The earliest application of *T. brontispae* against *B. longissima* was as early as 1920 in Indonesia (Leefmans, 1935; Lever 1936a, 1936b). Leefmans (1935) demonstrated that *T. brontispa* was the most effective biological agent against *B. longissima*. Other studies also indicated that *T. brontispa* had high potential as a biological control agent of the hispids. It was reported that this parasitoid efficiently controlled the pupae of *B. longissima* both in the laboratory as well as in the field. The percent of parasitization under laboratory conditions and in the field ranged from 76 - 87% and 35 - 74 % respectively. These results demonstrated the high potential of *T. brontispa* as a biological control agent against *B. longissima* (Meldy et al., 2004).

The introduction of *T. brontispae* against *B. longissima* in Sulawesi (formerly known as Celebes) started in 1932 (Meldy et al., 2004). Within three years, around 37,500 parasitized pupae were sent from Bogor to Makassar (Ujung Pandang). Eventually, ten rearing stations were established over South Sulawesi, and a total of around 13 million parasitized pupae were released between 1935 and 1941 in various locations. The rate of parasitization among field-collected pupae was between 70 - 90%. After a gap of 5 years, it was between 20 and 40%. In 1948-1949, the rate of parasitization reached ca. 40% in the 20 locations surveyed (Franssen and Tjoa, 1952). The establishment of *T. brontispae* brought *B. longissima* under control.

The eulophid *T. brontispae* was found to parasitize around 60-90% of the pupae and around 10% of the larvae of *B. longissima* (Kalshoven, 1981; Tjoa, 1953). About 20 wasps emerged from one *B. longissima* pupa in around 18-days (Chiu et al., 1988, Tjoa 1953). Hyperparasitoids had not yet been observed on any *T. brontispa* (Kalshoven, 1981, Tjoa; 1953; Lever, 1969).

Tetrastichus brontispa parasitizing the hispids in Pakuwon (West Java), Central Java and South Sulawesi was around 36.4%, 11.1% and 50.6, respectively. The level of parasitization was considered lower than that reported by Kalshoven (1981), who reported parasitization of 10% for larvae and 60-90%

for pupae. The differences could have been due to environmental conditions in every location, insects and plant biodiversity (Kalshoven, 1981).

On Banika Island (Russell Group, located in the Pacific Ocean), *T. brontispae* was first released against *B. longissima* in 1936 (Lever, 1937). In 1938, it was reintroduced in the Solomon Islands without controlling the Coconut Leaf beetle. Another introduction in 1968 succeeded and the parasitoid spread over 100 acres by the end of 1969, with effective control achieved and 70% parasitization. The parasitoid spread rapidly and greatly reduced the infestation (Stapley, 1973, 1979). This wasp was also imported to Rabaul (New Britain in Papua New Guinea) from the Solomon Islands in 1936. Large numbers were released near Rabaul and parasitized pupae were recovered (O'Connor, 1940; Froggatt and O'Connor, 1941).

On Saipan (Philippine Islands) and Rota Island (located in the Pacific Ocean), *T. brontispae*, obtained from Java, were released in 1948 for the control of *B. longissima*. The parasitoids appeared to be well established by 1954, sometimes providing parasitization of up to 90 % (Stapley, 1971, 1973, 1979). The rearing and release of the pupal parasitoid *T. brontispae* for the control *B. longissima* was recommended as an important hispid beetle management measure (Stapley, 1979).

Tetrastichus brontispae was introduced into the Noumea Peninsula, New Caledonia where it became established. However, the rate of parasitization did not exceed 24%, and even a combination with fungal diseases did not reduce the incidence of the pest to a satisfactorily low level, though no negative effects were observed (Cochereau, 1969).

In 1974, *T. brontispae* was introduced into Guam, New Hebrides, New Caledonia and the Solomon Islands with shipments from Saipan. The parasitoids became established and in the early 1980s, rates of parasitization ranging from 2 to 72 % in different locations were reported (Muniappan et al., 1980).

In Darwin, Australia, *T. brontispae* was imported from New Caledonia as a biological control agent against *B. longissima* in 1982 (Chin and Brown, 2001; Halfpapp, 2001) when it was first detected in 1979. The initial introduction was not successful, but a new introduction in 1984 established the wasps for five years before they disappeared (Halfpapp, 2001). *Tetrastichus brontispae* was reintroduced in Darwin in 1994 and established in moderate numbers for almost two years. Between October 1994 and March 1997, the beetle damage to the coconut palms was reduced by 20% at the sites where *T. brontispae* was released. The parasitoid became established in larger population at sites that were irrigated with overhead sprinklers. After November 1996, the numbers of *T. brontispae* diminished and the wasp could not be collected from any of the release sites or nearby areas. The climate at the northern tip of the Northern Territory may have been responsible for the parasitoid's failure to become established, as *T. brontispae* is probably better suited for a milder tropical climate (Chin and Brown, 2001). Only in North Queensland did the release of *T.*

brontispae demonstrate effective control of *B. longissima*. From the Australian experience, it was reported that successful releases were dependent on the initial release of large numbers of *T. brontispae* (Halfpapp, 2001).

In Samoa and American Samoa, *T. brontispae* have been mass-released since 1981 for the long-term control of *B. longissima*. From 1984 to 1987, a steady decline in damage was observed after the release of *T. brontispae* as well as the larval parasitoid, *Asecodes* sp. (Volgele and Zeddies, 1990). The incidence of palms damaged by *B. longissima* in plantations and villages was 4 and 22.9% respectively (Volgele and Zeddies, 1990). In American Samoa approximately 74 % of all the palms were infested, compared with only 14.3 % in Samoa. Damage to the total leaf area of coconut palms by *B. longissima* was 10% in American Samoa and only 1–2% in Samoa. A survey revealed that *Asecodes* sp. was an important cause of larval mortality in Samoa whereas no parasitoids were found in American Samoa (Volgele and Zeddies, 1990). An extensive survey of the 37,000 damaged trees in Western Samoa showed that *B. longissima* was under control and did not cause any significant yield losses (initial production losses were estimated to be as high as 50 – 70%). Since 1954, biological control has been a primary method of pest management in American Samoa (Tauili'ili and Vargo, 1993).

Ten releases of a total of 11,456 *T. brontispae* adults were made from January to July 1984 in Chenchinhu, Taiwan, and seven releases of 4,881 parasitoids were made from February to June 1984 in Linbien, Taiwan. The percentage parasitisation of pupae recorded from field recoveries at the two sites were 21 - 79% and 9 - 36%, respectively. The parasitoid prevented most host larvae from developing into adults at Chenchinhu, whereas at Linbien, the chrysomelid populations were not effectively suppressed (Chiu and Chen 1985). The parasitoid had established at distances of up to 2 - 8 km from the release site at Chenchinhu (Chiu et al., 1988). The establishment of *T. brontispae* as a biological control agent of *B. longissima* in Taiwan was confirmed by Chiu et al. (1988). *Tetrastichus brontispae* was introduced to Hainan, Mainland China, from Taiwan in 2004 (Fu and Xiong, 2004).

According to Heroetadji (1989), the parasitoid, *T. brontispae* parasitizes the larvae and pupae of *Plesispa reichei* and *P. nipae* as well as *B. longissima*. No negative effects were reported in countries where *T. brontispae* was released for hispid control in the last 50 years. The application of *A. hispinarum* and *T. brontispae* against *B. longissima* by different countries/regions is summarised in Table 3.

Table 3. The application of *Asecodes hispinarum* and *Tetrastichus brontispae* against *Brontispa longissima* for biological control by different countries/regions.

Country	Year of <i>B. longissima</i> invasion	Infestation of palm trees and losses incurred	Biological control
China	2002	The beetle occurred in 16 counties of Hainan province, infested about 817, 000 trees and endangered around 40,000 hectares (FAO 2004, Fu and Xiong 2004).	<i>Asecodes hispinarum</i> and entomopathogenic fungus <i>Metarhizium anisopliae</i> were tested. <i>Asecodes hispinarum</i> had been released in the north (Haikou), the south (Sanya) and the east (Qionghai) of the island since August 2004. Parasitization rate of 10-40 % was recorded. <i>Tetrastichus brontispae</i> was introduced from Taiwan and the studies to use them as biological control agent are in progress (Fu and Xiong, 2004).
Indonesia	1983	<i>Brontispa longissima</i> recorded in West and Central Java, S.E. Sulawesi, Bali, etc (FAO, 2004; Meldy et al., 2004).	Pupal parasitoid (<i>T. brontispae</i>), entomopathogenic fungi (<i>Metarhizium anisopliae</i> var. <i>anisopliae</i> and <i>Beauveria bassiana</i>) were used. Under field conditions, 35.7 to 73.6 % parasitisation of the hispid was achieved (Meldy et al., 2004).
Lao PDR People's Democratic Republic	2001	Infestation and damage in six villages within two provinces (Khennavong, 2004).	<i>Asecodes hispinarum</i> was introduced and released (Khennavong, 2004).

Maldives	1999	On Sun Island resort, Nalaguraidhoo and in South Ari Atoll (Shafia, 2004).	The parasitoid, <i>A. hispinarum</i> , was reared, released and established in Maldives (Liebregts and Chapman, 2004; Shafia, 2004).
Thailand	2000	Infestation of 7229 hectares worth US\$30 million of production affecting around 50,000 smallholder farmers (Sindhusakeand Winothai, 2004).	Rearing of <i>A. hispinarum</i> in August 2004 for release (Sindhusake and Winothai, 2004).
Vietnam	1999	Losses estimated at US\$17.8 million to the coconut industry in 2002 (Viet, 2004).	The parasitoid, <i>A. hispinarum</i> , was reared, released and established in Vietnam (Liebregts and Keith, 2004; Viet, 2004).

Conclusions and Recommendations

The Coconut Leaf Beetle, *B. longissima*, an endemic pest in Indonesia and Papua New Guinea, has devastated palms in many countries in and outside this region. Controlling this pest using natural enemies has proved effective. A literature review has indicated that *B. longissima* could be successfully brought under sustainable control by applying environmentally friendly classical biological control agents, such as *Asecodes hispinarum* and *Tetrastichus brontispae*, as shown in many Southeast Asian and Pacific countries.

Complete control of *B. longissima* with high cost/benefit ratio was achieved in several countries by importing and establishing parasitoids that attacked immature stages of the pest. The larval parasitoid *A. hispinarum*, collected and introduced in Vietnam, Maldives and Nauru to combat the beetle was quite successful in reducing the population of coconut hispids, resulting in great economic benefit. Other successful locations included some Pacific Islands, as well as East and Southeast Asian countries. The wasps are now being reared and released in Thailand, Laos, Cambodia, China, and Malaysia.

As compared to *A. hispinarum*, *T. brontispae* employed as a biocontrol agent to combat coconut hispid beetles had a longer history and proved to be the most effective biocontrol agent against the coconut hispid beetles as early as 1920. The results of biological experiments involving the parasitoids showed that both *A. hispinarum* and *T. brontispae* had wide ranges of adaptation to temperature, thermal tolerance, short developmental time and high reproductive capacity. In addition, both *A. hispinarum* and *T. brontispae* had reasonable

parasitic rates against their host insects (Chalerm and Amporn, 2004; Chen et al., 2010; Htwe et al., 2013; Liu et al. 2005 a, 2008; Lu et al., 2005b; Sun et al., 2011; Tang et al., 2006; Tang et al., 2007a, 2007b; Pundee, 2009; Viet, 2004).

This literature review has revealed that *A. hispinarum* and *T. brontispae* have been used as biocontrol agents against *B. longissima*. Results of our observations in Singapore of more than 20 generations of *A. hispinarum* were not associated with any harmful microbes or other hyperparasitoids. With a very narrow host range and either monophagous or oligophagous, these parasitoids die off once the host population has reached a low threshold. Therefore, releasing these two parasitoids for control of *B. longissima* offers a safe and effective alternative with minimal impact to the environment.

Natural enemies attacking only a single stage of the pest might not achieve satisfactory *B. longissima* control, as results from South Sulawesi indicated that the pest had overlapping generations. Hence better control would be envisioned when both the larval parasitic wasps, *A. Hispinarum*, and pupal parasitic wasps, *T. brontispae* are used concurrently as biological control agents against *B. longissima*.

Parasitism commonly results in a unique array of host physiological responses and adaptations. These physiological changes are often manifested by altered host behaviour. The functional and evolutionary relationships between the two species of parasitoids and their host insects, hispid beetles, need to be studied further. Physiological effects may be assessed as to whether they affect fitness and confer benefit or harm to one or both of the symbionts involved. It would be useful if these physiological responses, specifically neural, endocrine, neuromodulatory and immunomodulatory components which may interact to modify host behaviours, are examined. Results of adaptation strategies of hispids to both parasitic wasps and host plants can vastly improve the efficacy of future hispid biological control programmes.

Acknowledgements

The authors wish to express their appreciation to Dr. Varughese Philip and Dr. Mohamed Ali of Agri-Food & Veterinary Authority, Singapore for critically editing the manuscript.

Literature Cited

- AVA (Agri-Food & Veterinary Authority, Singapore). 2011. Development of standard protocol for mass rearing of *Asecodes hispinarum* Boucek and *Tetrastichus brontispa* Ferriere for biological control of *Brontispa longissima* on palms. Entomology & Nematology Branch, Animal & Plant Health Laboratories Division, Agri-Food & Veterinary Authority, Singapore. Unpublished Report. 13 pp.
- Baringbing, B. and E. Karmawati. 1992. Effects of diflubenzuron on the coconut pest *Brontispa longissima*, Gestro and its parasite, *Tetrastichus brontispae* Ferriere. *Industrial Crops Research Journal* 4:40-43.
- Barratt, B. I. P., C. M. Ferguson, M. R. McNeil, and S. L. Goldson. 1999. Parasitoid host specificity testing to predict field host range. pp. 70-83. In, *Recommendations for Host Specificity Testing in Australia: Towards Improved Assays for Biological Control*. Whithers, T. M., L. Barton Browne, and J. N. Stanley (Editors). CRC Tropical Pest Management. Brisbane, Australia. 742 pp.

- Berkvens, N., J. Baverstock, P. De Clercq, M. E. N. Majerus, J. K. Pell, H. E. Roy, L. Tirry, and P. M. Wells. 2009. Good and bad traits of *Harmonia axyridis* – from biological control to invasion. pp. 393-402. In, *Proceedings of the third International Symposium on Biological Control of Arthropods*. Christchurch, New Zealand. February 8-13, 2009. 636 pp. <https://biblio.ugent.be/publication/537239>
- Blossey, B. 1995. Host specificity screening of insect biological weed control agents as part of an environmental risk assessment. pp. 84-89. In, *Biological control: benefits and risks*. Hokkanen, H. M. T. and J. M. Lynch (Editors). Cambridge University Press. Cambridge, England, United Kingdom. 304 pp. <http://dx.doi.org/10.1017/CBO9780511661730.010>
- Boucek, Z. 1988. Australasian Chalcidoidea (Hymenoptera). A biosystematic revision of genera of fourteen families, with a reclassification of species. CAB International. Wallingford, Oxon, United Kingdom. 832 pp.
- CFC/DFID/APCC/FAO. 2004. *Annual Report. Project on Coconut Integrated Pest Management*. Asian and Pacific Coconut Community. Jakarta, Indonesia. 192 pp.
- CABI. 2014. *Brontispa longissima*. In, *Invasive species compendium. Datasheets, maps, images, abstracts and full text on invasive species of the world*. <http://www.cabi.org/isc/datasheet/10059>
- Chen, Q., Z. Peng, C. Xu, B. Lu Tang, Q. Jin, H. Wen, and F. Wen. 2010. Biological assessment of *Tetrastichus brontispae*, a pupal parasitoid of coconut leaf beetle *Brontispa longissima*. *Biocontrol Science and Technology* 20(3/4):283-295. <http://dx.doi.org/10.1080/09583150903503323>
- Chin, D. and H. Brown. 2001. Biological control of palm leaf beetle, *Brontispa longissima* (Gestro) (Coleoptera: Chrysomelidae) with the wasp parasitoid, *Tetrastichus brontispae* (Ferriere) (Hymenoptera: Eulophidae) in Darwin. pp. 61-65. In, *Proceedings of the Sixth Workshop for Tropical Agricultural Entomology*. Darwin, Australia, 11-15 May 1998. *Technical Bulletin Department of Primary Industry and Fisheries, Northern Territory of Australia*. No. 288. 151 pp.
- Chiu, S. C. and B. H. Chen. 1985. Importation and establishment of *Tetrastichus brontispae*, a parasitoid of the coconut beetle, in Taiwan. pp. 12-13. In, *A review of the biological control of crop pests in Taiwan (1981-1984)*. Special Publication. Taiwan Agricultural Research Institute (Taichung). 33 pp.
- Chiu, S. C., Z. C. Chen, L. Y. Chou, K. C. Chou, and C. M. Chen. 1988. Biological control of coconut leaf beetle in Taiwan. *Journal of Agricultural Research of China* 37(2): 211 - 219
- Cochereau, P. 1969. Installation of *Tetrastichus brontispae* Ferr. (Hymenoptera, Eulophidae) parasite of *Brontispa longissima* Gestro, var. *froggatti* Sharp (Coleoptera, Chrysomelidae, Hispinae) in the peninsula of Noumea. (Installation de *Tetrastichus brontispae* Ferr. (Hymenoptera, Eulophidae), parasite de *Brontispa longissima* Gestro, var. *froggatti* Sharp (Coleoptera, Chrysomelidae, Hispinae) dans la presqu'île de Noumea). *Cahiers ORSTROM, Serie Biologie* 7:139-141.
- Convention on Biological Diversity (CBD). 2002. Sixth Conference of the Parties, The Hague, the Netherlands, 7 - 19 April 2002: Decision VI/23—Alien species that threaten ecosystems, habitats or species to which is annexed Guiding principles for the prevention, introduction and mitigation of impacts of alien species that threaten ecosystems, habitats or species (<http://www.biodiv.org/>). Annex 1, pp. 155–77.
- DeBach, P. and J. R. Quezada. 1973. Bioecological and population studies of the cottony-cushion scale, *Icerya purchasi* Mask and its natural enemies, *Rodolia cardinalis* Mulsant and *Cryptochaetum iceryae* Williston in southern California. *Hilgardia* 41:629-688.
- Ding, B-J., C-X. Li, M-G. Liang, Z-Y. Liang, W-Q. Qin, and Z-L. Ma. 2007. Biological control of *Brontispa longissima* by releasing *Tetrastichus brontispae* in urban zones of Shenzhen. *Chinese Journal of Biological Control* 23(4):306-309.
- Eilenberg J., A. Hajek, and C. Lomer. 2001. Suggestions for unifying the terminology in biological control. *BioControl* 46:387–400. <http://dx.doi.org/10.1023/A:1014193329979>

- FAO (Food and Agriculture Organization of the United Nations). 1981. The coconut hispine, *Brontispa longissima*. Quarterly Newsletter, FAO Plant Protection Committee for the South East Asia and Pacific Region 24:9-10.
- FAO (Food and Agriculture Organization of the United Nations). 2004. Report of the Expert Consultation on Coconut Beetle Outbreak in APPPC Member Countries. 26-27 October 2004. Bangkok, Thailand. 147 pp. <http://www.fao.org/docrep/007/ad522e/ad522e00.htm>
- Ferriere, C. 1933. Chalcidoid and proctotrupoid parasites of pests of the coconut palm. *Stylops* 2(4-5):86-96, 97-108.
- Flint, Maria Louise and Dreistadt, Steve H. 1998. *Natural Enemies Handbook: The Illustrated Guide to Biological Pest Control*. University of California Press. 154 pp.
- Franssen, C. J. H. and T. M. Tjoa. 1952. Biologische be strijding van de klapperplagen op Zuid-Celebes. (Biological control of the coconut pests in South Sulawesi.) *Landbouw* (Jakarta, Indonesia) 24(7-12):319-360.
- Froggatt, J. L. and B. A. O'Connor. 1941. Insect associated with the coconut palm. Part II. New Guinea *Agricultural Gazette* 7:125-130.
- Fu, Y. and Y. Xiong. 2004. Occurrence and control of coconut leaf beetle in China. pp. 35-38. In, FAO (Food and Agriculture Organization of the United Nations). *Report of the Expert Consultation on Coconut Beetle Outbreak in APPPC Member Countries*. 26-27 October 2004. Bangkok, Thailand. 147 pp. <http://www.fao.org/docrep/007/ad522e/ad522e00.htm>
- Gourves, J., G. A. Samuelson, C. H. Boheman, and H. Fairmaire. 1979. The Chrysomelidae of Tahiti (Coleoptera) (Les Chrysomelidae de Tahiti [Coleopteres]). *Pacific Insects* 20(4):410-415.
- Grandgirard, J., M. S. Hoddle, J. N. Petit, G. K. Roderick, and N. Davies. 2008. Engineering an invasion: Classical biological control of the glassy-winged sharpshooter, *Homalodisca vitripennis*, by the egg parasitoid *Gonatocerus ashmeadi* in Tahiti and Moorea, French Polynesia. *Biological Invasions* 10:135-148. <http://dx.doi.org/10.1007/s10530-007-9116-y>
- Greathead, D. J. 1986. Parasitoids in classical biological control. pp. 289-318. In, *Insect Parasitoids*. Waage, J. and D. Greathead (Editors). Academic Press. London, England, UK. 389 pp.
- Greathead, D. J. 1995. Benefits and risks of classical biological control. In: *Biological Control: Benefits and Risks*, pp. 53-63. Hokkanen, H. M. T., and Lynch, J. M., Eds., Cambridge University Press, Cambridge, UK.
- Gurr G. and S. Wratten (Editors). 2000. *Biological Control: Measures of Success*. Kluwer. Dordrecht, The Netherlands. 448 pp. <http://dx.doi.org/10.1007/978-94-011-4014-0>
- Gurr, G., N. D. Barlow, J. Memmott, S. D. Wratten, and D. J. Greathead. 2000. A history of methodical, theoretical and empirical approaches to biological control, pp 3-37. In, Gurr, G. and S. Wratten (Editors). *Biological Control: Measures of Success*. Kluwer Academic Publishers. Dordrecht, The Netherlands. 448 pp. http://dx.doi.org/10.1007/978-94-011-4014-0_1
- Gutierrez, J. 1978. Biological control of the coconut hispid (*Brontispa longissima*) and a survey of fruit flies in American Samoa. OSTROM. South Pacific Commission. Noumea, New Caledonia. 10 pp.
- Halfpapp, K. 2001. Introduction of *Tetrastichus brontispae* for control of *Brontispa longissima* in Australia. pp. 59-60. In, *Proceedings of the Sixth Workshop for Tropical Agricultural Entomology*. Darwin, Australia, 11-15 May 1998. *Technical Bulletin Department of Primary Industry and Fisheries, Northern Territory of Australia*. No. 288. 151 pp.
- Hall, R. W. and L. E. Ehler. 1979. Rate of establishment of natural enemies in classical biological control. *Bulletin of the Entomological Society of America* 25:280-282.
- Hall, R. W., L. E. Ehler, and B. Bisabri-Ershadi. 1980. Rate of success in classical biological control of arthropods. *Bulletin of the Entomological Society of America* 26:111-114.
- Hawkins, B. A. and H. V. Cornell. 1994. Maximum parasitism rates and successful biological control. *Science* 266(5192):1886. <http://dx.doi.org/10.1126/science.266.5192.1886>
- Hawkins, B. A., M. B. Thomas, and M. E. Hochberg. 1993. Refuge theory and biological control. *Science* 262:1429-1432. <http://dx.doi.org/10.1126/science.262.5138.1429>
- Haye, T., P. G. Mason, and U. Kuhlmann. 2009. Predictive value of biological control agent's attributes for introduction: *Peristenus digoneutis* as a case study. . Proceedings of the 3rd

- International Symposium on Biological Control of Arthropods, Christchurch, New Zealand, 8-13 February, 2009 2009 pp. 403-415.
- He L. S., K. H. Ong, C. P. Yik, Y. K. Fong, and H. J. A. Chan. 2006. Chemical control of hispid beetles (*Brontispa longissima*) on palms, *Singapore Journal of Primary Industries* 32(2005/06):80-92.
- Heroetadji, H. 1989. Parasites of *Plesispa reichei* and *Brontispa longissima* in East Java. pp. 92-96. In, *Integrated Coconut Pest Control Project. UNDP/FAO (Food and Agriculture Organization of the United Nations)*. Annual Report. Coconut Research Institute. Manado, North Sulawesi, Indonesia.
- Hollingsworth, R. S. Meleisea, and T. Iosefa. 1988. Natural enemies of *Brontispa longissima* (Gestro) in West Samoa. *Alafua Agricultural Bulletin* 13(1):41-45.
- Htwe, A. N., M. Murata, S. Takano, and S. Nakamura. 2013. Effects of constant and fluctuating temperatures on development of the coconut hispine beetle, *Brontispa longissima* (Coleoptera: Chrysomelidae) and two species of parasitoid. *Biocontrol Science and Technology* 23(5):574-583. <http://dx.doi.org/10.1080/09583157.2013.788132>
- Huang, S.-c., W.-q. Qin, H.-q. Zhou, Z.-l. Ma, and C.-x. Li. 2007. Study on reproductive biology of *Tetrastichus brontispae*. *Entomological Journal of East China*. 2007 Issue 3. http://en.cnki.com.cn/Article_en/CJFDTOTAL-HDKC200703002.htm and http://en.cnki.com.cn/Journal_en/D-D046-HDKC-2007-03.htm
- Huffaker, C. B. 1977. *Theory and Practice of Biological Control*. Academic Press Inc. Ltd. London, England, UK. 810 pp.
- Hunt, E. J., U. Kuhlmann, A. Sheppard, T. K. Qin, B. Barratt, L. Harrison, P. G. Mason, D. Parker, J. Goolsby, and B. Flanders. 2008. Regulation of invertebrate biological control agents in Australia, New Zealand, Canada and the USA: recommendations for Europe in its pursuit of a harmonised regulatory system. *Journal of Applied Entomology* 132:89-123. <http://dx.doi.org/10.1111/j.1439-0418.2007.01232.x>
- International Plant Protection Convention (IPPC). 2005. International Standards for Phytosanitary Measures. ISPM No. 3. Guidelines for the export, shipment, import and release of biological control agents and beneficial organisms. Produced by the Secretariat of the International Plant Protection Convention. FAO 2006. 32 pp.
- Jetter, K., K. Klonksy, and C. H. Pickett. 1997. A cost/benefit analysis of the ash whitefly biological control program in California. *Journal of Arboriculture* 23: 65-72.
- Kalshoven, L. G. E., P. A. van der Laan, and G. H. L. Rothschild. 1981. *The Pests of Crops in Indonesia*. Ichtia Baru Van Hoeve. Jakarta, Indonesia. 701 pp.
- Khennavong, V. 2004. The status of *Brontispa longissima* coconut beetle outbreak in Lao PDR. pp. 51-56. In, FAO (Food and Agriculture Organization of the United Nations). *Report of the Expert Consultation on Coconut Beetle Outbreak in APPPC Member Countries*. 26-27 October 2004. Bangkok, Thailand. 147 pp. <http://www.fao.org/docrep/007/ad522e/ad522e00.htm>
- Leefmans, S. 1935. Biologische bestrijding van insectenplagen in Nederlandsch-Indie door interinsulaire overbrenging van parasieten. [Biological control of insect pests in the Dutch East-Indies through inter-island transfer of parasites]. *Landbouwkundig Tijdschrift* 47(571): 209-219.
- Lever, R. J. A. W. 1937. Economic insects and biological control in the British Solomon Islands. *Bulletin of Entomological Research* 28: 325-331. <http://dx.doi.org/10.1017/S0007485300038475>
- Lever, R. J. A. W. 1969. *Pests of the Coconut Palm*. No. 18. FAO. Rome, Italy. 190 pp.
- Li C.-x., W.-q. Qin, S.-c. Huang, C.-w. Han, Z.-l. Ma, and Z.-q. Peng. 2008. Effect of parasitic wasps on control of *Brontispa longissima* (Gestro) in Hainan Province. *China Forestry Science and Technology* 22(1):41-44.
- Liebrechts, W. and K. Chapman. 2004. Impact and control of the coconut hispine beetle, *Brontispa longissima* Gestro (Coleoptera: Chrysomelidae). pp. 19-25. In, FAO (Food and Agriculture Organization of the United Nations). *Report of the Expert Consultation on Coconut Beetle Outbreak in APPPC Member Countries*. 26-27 October 2004. Bangkok, Thailand. 147 pp. <http://www.fao.org/docrep/007/ad522e/ad522e00.htm>

- Liebrechts, W., T. T. Viet, and K. Chapman. 2006. Mass rearing of the coconut hispine beetle (*Brontispa longissima*) and its natural enemy (*Asecodes hispinarum*). *FAO (Food and Agriculture Organization of the United Nations). Regional Office for Asia and the Pacific*. Bangkok, Thailand. 25 pp.
- Liu, K., J.-R. Lin, Y.-G. Fu, Z.-Q. Peng, and Q.-A. Jin. 2008. Effects of parasitization by *Tetrastichus brontispae* (Hymenoptera: Eulophidae) on immunoreaction of the coconut hispine beetle, *Brontispa longissima* (Coleoptera: Chrysomelidae). *Acta Entomologica Sinica* 51(10):1011-1016.
- Lonsdale W. M., Briese D. T., and Cullen J. M. 2001. Risk analysis and weed biological control. pp. 185–210. In, *Evaluating indirect ecological effects of biological control*. Wajnberg, E., J. K. Scott, and P. C. Quimby (Editors). CABI Publishing. Wallingford, Oxon, England, United Kingdom. 261 pp.
- Louda S. M., R. W. Pemberton, M. T. Johnson, and P. A. Follett. 2003. Nontarget effects: the Achilles' heel of biological control? *Annual Review Entomology* 48:365–96. <http://dx.doi.org/10.1146/annurev.ento.48.060402.102800>
- Lu, B.-Q., Y.-Q. Chen, Y. Ban, R.-D. Han, and Z.-Q. Peng. 2005a. The feasibility of the controlling coconut leaf beetle (*Brontispa longissima*) with introducing natural enemies *Asecodes hispinarum*. *Chinese Bulletin of Entomology* 42(3):254-258.
- Lu, B.-Q., Z.-Q. Peng, C. Tang, H.-B. Wen, Q.-A. Jin, Y.-G. Fu, and Y.-Z. Du. 2005b. Biological characteristics of *Asecodes hispinarum* Bouček (Hymenoptera: Eulophidae), a parasitoid of *Brontispa longissima* (Gestro) (Coleoptera: Hispididae). *Acta Entomologica Sinica* 48(6):943-948.
- Lu, B. Q., Z. Q. Peng, Ch. A. Xu, C. Tang, Y. G. Fu, Y. Z. Du, and F. H. Wan. 2006. Biological characteristics of *Tetrastichus brontispae* Ferriere (Hymenoptera: Eulophidae), a parasitoid of *Brontispa longissima* (Gestro) (Coleoptera: Hispididae). *Acta Entomologica Sinica* 49:643–649.
- Lu, B., C. Tang, Z. Peng J. La Salle, and F. Wan. 2008. Biological assessment in quarantine of *Asecodes hispinarum* Bouček (Hymenoptera: Eulophidae) as an imported biological control agent of *Brontispa longissima* (Gestro) (Coleoptera: Hispididae) in Hainan, China. *Biological Control* 45(1):29–35. <http://dx.doi.org/10.1016/j.biocontrol.2007.11.008>
- Lynch, L. D., H. M. T. Hokkanen, D. Babendrier, F. Bigler, G. Burgio, Z.-H. Gao, S. Kuske, A. Loomans, I. Menzler-Hokkanen, M. B. Thomas, G. Tommasini, J. K. Waage, J. C. van Lenteren, and Q. Q. Zeng. 2001. Insect biological control and non-target effects: a European perspective. pp. 99-125. In, *Evaluating Indirect Ecological Effects of Biological Control*. Wajnberg, E., J. K. Scott, and P.C. Quimby (Editors). CABI Publishing. Wallingford, Oxon, England, UK. 261 pp.
- Ma, Z., X. Zhou, S. Zhao, C. Li, and G. Huang. 2006a. Effect of temperature on developmental time and parasitizing capacity of *Tetrastichus brontispae* Fer. *Chinese Journal of Tropical Crops* 2006 (3):61-65.
- Ma Z., S. Zhao, W. Qin, C. Han, and G. Huang. 2006b. The dispersal distance test of *Tetrastichus brontispae* in the field, a natural enemy of Coconut Leaf Beetle *Brontispa longissima*. *Chinese Journal of Biological Control* 22(S1):11-13.
- Meldy L. A. H., J. C. Alouw, and H. Novariant. 2004. Biological control of *Brontispa longissima* (Gestro) in Indonesia. pp. 39-52. In, *FAO (Food and Agriculture Organization of the United Nations). Report of the Expert Consultation on Coconut Beetle Outbreak in APPPC Member Countries*. 26-27 October 2004. Bangkok, Thailand. 147 pp. <http://www.fao.org/docrep/007/ad522e/ad522e00.htm>
- Muniappan, R., J. G. Duenos, and T. Blas. 1980. Biological control of the Palau coconut beetle *Brontispa palauensis* (Esaki and Chujo), on Guam. *Micronesia* 16:359-360.
- Murdoch, W. W. 1994. Population regulation in theory and practice. *Ecology* 75:271-287. <http://dx.doi.org/10.2307/1939533>
- Murray, T. J., S. Mansfield, and T. M. Withers. 2009. Comparing the behavioural strategies of two parasitoid wasps: Is aggressive resource defending good for biological control. In, *Proceedings of the third International Symposium on Biological Control of Arthropods*. Christchurch, New Zealand. February 8-13, 2009. 636 pp.

- Nakamura, S., R. Ichiki, S. Takano, M. Murata, N. T. Huong, A. Mochizuki, K. Takasu, K. Konishi, J. C. Alouw, and D. S. Pandin. 2012. Two cryptic species in the coconut hispine beetle, *Brontispa longissima*. Research Highlights 2012. Japan International Research Center for Agricultural Sciences. http://www.jircas.affrc.go.jp/english/publication/highlights/2012/2012_08.html
- Neuenschwander, P. 2001. Biological control of the Cassava Mealybug in Africa: A Review. *Biological Control* 21:214-229. <http://dx.doi.org/10.1006/bcon.2001.0937>
- Neuenschwander, P. and R. Markham. 2001. Biological control in Africa and its possible effects on biodiversity. pp. 127-146. In, Wajnberg, E., J. K. Scott, P. C. Quimby (Editors). *Evaluating Indirect Ecological Effects of Biological Control*. CAB International, University Press. Cambridge, England, UK. 261 pp.
- Norgaard, R. B. 1988. Economics of the cassava mealybug (*Phaenacoccus manihoti*; Hom. Pseudococcidae) biological control program in Africa. *Entomophaga* 33:3-6. <http://dx.doi.org/10.1007/BF02372307>
- O'Connor, B. A. 1940. Notes of the coconut leaf hispid, *Brontispa froggatti* Sharp and its parasites. *New Guinea Agricultural Gazette* 6:36-40.
- Pickett, C. H., J. C. Ball, K. C. Casanave, K. Klonksy, K. M. Jetter, L. G. Bezark, and S. E. Schoenig. 1996. Establishment of the ash whitefly parasitoid *Encarsia inaron* (Walker) and its economic benefits to ornamental street trees in California. *Biological Control* 6:260-272. <http://dx.doi.org/10.1006/bcon.1996.0033>
- Pundee, T. 2009. Biological study of larval parasitoid, *Asecodes hispinarum* Bouček (Hymenoptera: Eulophidae) and pest management program for major insect pests of coconut in a golf course. Doctor of Philosophy (Entomology), Major Field: Entomology, Department of Entomology. Graduate School, Kasetsart University (Nangkok, Thailand). Ph.D. Dissertation 136 pp. <http://research.rdi.ku.ac.th/world/cache/99/ThitrapornPunAll.pdf>
- Pundee, T., S. Jamornmarn, W. Chongrattanameteekul, C. Sindhusake, A. Winotai, and R. Morakote. 2009. Biological control of the coconut hispine beetle, *Brontispa longissima* Gestro (Coleoptera; Chrysomelidae) by the parasitoid *Asecodes hispinarum* Bouček (Hymenoptera: Eulophidae) on a golf course. *Kasetsart Journal: Natural Sciences* 43:261-268.
- Rethinam, P. and S. P. Singh. 2007. Current status of the coconut beetle outbreaks in the Asia-Pacific region. In, *Developing an Asia-Pacific strategy for forest invasive species: The coconut beetle problem – bridging agriculture and forestry*. 154 pp. <http://www.fao.org/docrep/010/ag117e/ag117e00.htm>, <ftp://ftp.fao.org/docrep/fao/010/ag117e>
- Qian, J., Z. Gou, X. Qian, and X. Luo. 2011. Control effect of *Asecodes hispinarum* mixed with *Tetrastichus brontispae* against *Brontispa longissima*. *Acta Agriculturae Jiangxi* 2011-03
- Shafia, A. 2004. Integrated control of coconut hispid beetle *Brontispa longissima* (Gestro) in the Maldives. pp. 67-74. In, FAO (Food and Agriculture Organization of the United Nations). *Report of the Expert Consultation on Coconut Beetle Outbreak in APPEC Member Countries*. 26-27 October 2004. Bangkok, Thailand. 147 pp. <http://www.fao.org/docrep/007/ad522e/ad522e00.htm>
- Sindhusake, C. and A. Winothai. 2004. Outbreaks and management of coconut hispine beetle (*Brontispa longissima*) Thailand. pp. 82-89. In, FAO (Food and Agriculture Organization of the United Nations). *Report of the Expert Consultation on Coconut Beetle Outbreak in APPEC Member Countries*. 26-27 October 2004. Bangkok, Thailand. 147 pp. <http://www.fao.org/docrep/007/ad522e/ad522e00.htm>
- Singh, S.P. and P. Rethinam. 2004a. Baculovirus-A key component of biointensive integrated pest management of rhinoceros beetle. *Cocoinfo International* 11(1):25-28.
- Singh, S. P. and P. Rethinam. 2004b. Use of green muscardine fungus in BIPM of rhinoceros beetle. *Cocoinfo International* 11(2):19-24.
- Smith, R. F. 1968. Recent developments in integrated control. Proceedings of the Fourth British Insecticide and Fungicide Conference. 20th-23rd November 1967. Hotel Metropole. Brighton, England, UK. 2:464-71.
- Staines, C. L. 2012. Catalog of the hispines of the world (Coleoptera: Chrysomelidae: Cassidinae). Tribe Cryptonychini. http://entomology.si.edu/Collections_Coleoptera-Hispines.html

- Stapley J. H. 1971. The introduction and establishment of the *Brontispa* parasite in the Solomon Islands. *South Pacific Commission Information Circular* 30:2-6.
- Stapley, J. H. 1973. Insect pests of coconuts in the Pacific region. *Outlook on Agriculture* 7(5):211-217.
- Stapley, J. H. 1979. Notes on biological control in the Solomon Islands. IOBC (International Organisation for Biological and Integrated Control) Newsletter 1979(11/12):4-5.
- Sun, R.-F., X-Q. Tian, X.-M. Zhang, Y.-C. Li, F. Quan, and L. Zhu. 2011. Comparisons of the field and laboratory populations of *Asecodes hispinarum* Boucek. *Chinese Journal of Applied Entomology* 48(4):934-940.
- Tang, C., Z. Q. Peng, K. H. Wu, Y. J. Liang, Y. G. Fu, and F. H. Wan. 2006. The effect of sublethal doses of insecticides on the functional response of *Asecodes hispinarum*. *Chinese Bulletin of Entomology* 43(5):644-647. [in Chinese]
- Tang, C., Z. Q. Peng, Q.-A. Jin, Y. G. Fu, and F. H. Wan. 2007a. Effects of variable temperature on development of *Asecodes hispinarum* (Hymenoptera: Eulophidae). *Acta Phytophylacica Sinica* 34(1):1-4. [in Chinese]
- Tang, C., Z. Q. Peng, K. N. Chen, B. Q. Lu, Q. A. Jin, J. Zhou, Y.G. Fu, and F.H. Wan. 2007b. Influence of temperature on functional response of *Asecodes hispinarum*. *Chinese Journal of Biological Control* 23(1):11-13. [in Chinese]
- Tauili'i-ili P. and R. M. Vargo. 1993. History of biological control in American Samoa. *Micronesica Supplement* 4:57-60.
- Tjoa, T. M. 1953. *Memberantas hama-hama kelapa dan kopra*. Noordhoff-Kolff. Jakarta, Indonesia. 270 pp.
- Tjoa, T. M. 1965. The occurrence of two strains of *Brontispa longissima* (Gestro) (Coleoptera: Hispidae) based on resistance or non-resistance to the parasite *Tetrastichus brontispae* (Ferr.) (Hymenoptera: Eulophidae) in Java. *Bulletin of Entomological Research* 55: 609-614. <http://dx.doi.org/10.1017/S0007485300049713>
- van Lenteren, J. C. 1995. Integrated pest management in protected crops. pp. 311-343. In, *Integrated Pest Management*. Dent, D. and N. C. Elliott (Editors). Chapman and Hall. New York, NY, USA. 356 pp.
- van Lenteren, J. C. and J. Woets. 1988. Biological and integrated pest control in greenhouses. *Annual Review of Entomology* 33:239-269. doi:10.1146/annurev.en.33.010188.001323
- van Lenteren, J. C. 2000. A greenhouse without pesticides: fact or fantasy? *Crop Protection* 19, 375-384. doi:10.1016/S0261-2194(00)00038-7
- van Lenteren, J. C. 2003. Environmental risk assessment of exotic natural enemies used in inundative biological control. *BioControl* 48, 3-38. doi:10.1023/A:1021262931608
- van Lenteren, J. C. 2006. How not to evaluate augmentative biological control. *Biological Control* 39:115-118. <http://dx.doi.org/10.1016/j.biocontrol.2006.05.014>
- van Lenteren, J. C., J. S. Bal, F. Bigler, H. M. T. Hokkanen, and A. J. M. Looman. 2006a. Assessing risks of releasing exotic biological control agents of arthropod pests. *Annual Review of Entomology* 51:609-634. doi:10.1146/annurev.ento.51.110104.151129
- van Lenteren, J. C., M. J. W. Cock, T. S. Hoffmeister, and D. P. A. Sands. 2006b Host specificity in arthropod biological control, methods for testing and interpretation of the data. pp. 38-63. In, *Environmental impact of invertebrates for biological control of arthropods: methods and risk assessment*. Bigler, F., D. Babendreier and U. Kuhlmann (Editors). CAB International. Wallingford, England, UK 299 pp. <http://dx.doi.org/10.1079/9780851990583.0038>
- Viet, T. T. 2004. Classical biological control of coconut hispine beetle with the parasitoid *Asecodes hispinarum* Boucek (Hymenoptera: Eulophidae) in Vietnam. pp. 90-99. In, FAO (Food and Agriculture Organization of the United Nations). *Report of the Expert Consultation on Coconut Beetle Outbreak in APPEC Member Countries*. 26-27 October 2004. Bangkok, Thailand. 147 pp. <http://www.fao.org/docrep/007/ad522e/ad522e00.htm>
- Volgele, J. M. 1989. Biological control of *Brontispa longissima* in Western Samoa: an ecological and economic evaluation. *Agriculture, Ecosystems and Environment* 27:315-329. [http://dx.doi.org/10.1016/0167-8809\(89\)90095-9](http://dx.doi.org/10.1016/0167-8809(89)90095-9)

- Volgele, J. M, and J. Zeddies. 1990. Economic analysis of classical biological pest control: a case study from Western Samoa. *Deutsche Landwirtschafts-Gesellschaft* 1:45-51.
- Wapshere, A. J. 1974. A strategy for evaluating the safety of organisms for biological weed control. *Annals of Applied Biology* 77:201-11. <http://dx.doi.org/10.1111/j.1744-7348.1974.tb06886.x>
- Wood, B. J. 2002. Pest control in Malaysia's perennial crops: A half century perspective tracking the pathway to Integrated Pest Management. *Integrated Pest Management Reviews* 7(3):173-190. <http://dx.doi.org/10.1023/B:IPMR.0000027501.91697.49>
- Xu, C.-A., Y. Chan, Z.-Q. Peng, H.-B. Wen, Y.-G. Fu, and F.-H. Wan. 2008. Effect of cold storage on the population quality of *Tetrastichus brontispae*. *Chinese Bulletin of Entomology* 45(1):112-116. [in Chinese]
- Zhou, X., G. Huang, Z. Ma, S. Zhao, and H. Zhou. 2006. Host preference, suitability and functional response of *Tetrastichus brontispae* Ferrière. (Hymenoptera: Eulophidae). *Chinese Journal of Tropical Crops* 2:74-77.