PLUTELLA MACULIPENNIS, CURT., ITS NATURAL AND BIOLOGICAL CONTROL IN ENGLAND.

By J. ELIOT HARDY, D.Sc., M.A. (Cantab.), F.R.E.S.
Zoological Department, Charles University, Prague, and Farnham House Laboratory, Imperial Institute of Entomology.

(PLATE IX.)

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1. Introduction.

The Diamond-back Moth, *Plutella maculipennis*, Curt., is a small Tineid moth of unusually wide distribution throughout the world. Its importance lies in the fact that it feeds on cruciferous crops and, although in most countries it is limited to small proportions, periodical infestations occur in which much damage is done. Fifty or sixty years ago the moth became established in New Zealand, where it spread over both islands, soon reaching pest proportions. In this new habitat *Plutella* permanently maintained a very high level and was not subjected to the same degree of control as in other countries. Investigation showed that, while in most other areas *Plutella* is largely destroyed by parasites, no such enemies of any significance existed in New Zealand, and the absence of this factor was probably of

extreme importance. The problem therefore appeared to be well suited for the application of the biological method of control.

The New Zealand Government therefore applied to the Imperial Institute of Entomology for a supply of the parasites of *Plutella maculipennis*. During the course of the work the writer had occasion to gather some facts, not noted by previous workers, which appear to throw some light on the problem of the natural control of Lepidopterous pests in general and the Diamond-back Moth in particular.

The following pages describe the practical work involved in obtaining suitable parasites from England for introduction into New Zealand, and also experimental research on the moth in its English habitat.

2. Description of Plutella maculipennis, its Life-history and Distribution.

The Diamond-back Moth is well-known and has been frequently described by Lepidopterists; only a brief description will be given here.

The adult moth (fig. 1) is a small, slender, greyish-brown insect, having a wing expanse of about 10 mm. When at rest the wings are closely applied to the sides of the insect, meeting above the body and presenting a slightly turned-up appearance at the rear end. A creamy-yellow band, extending from the base of the tornus,

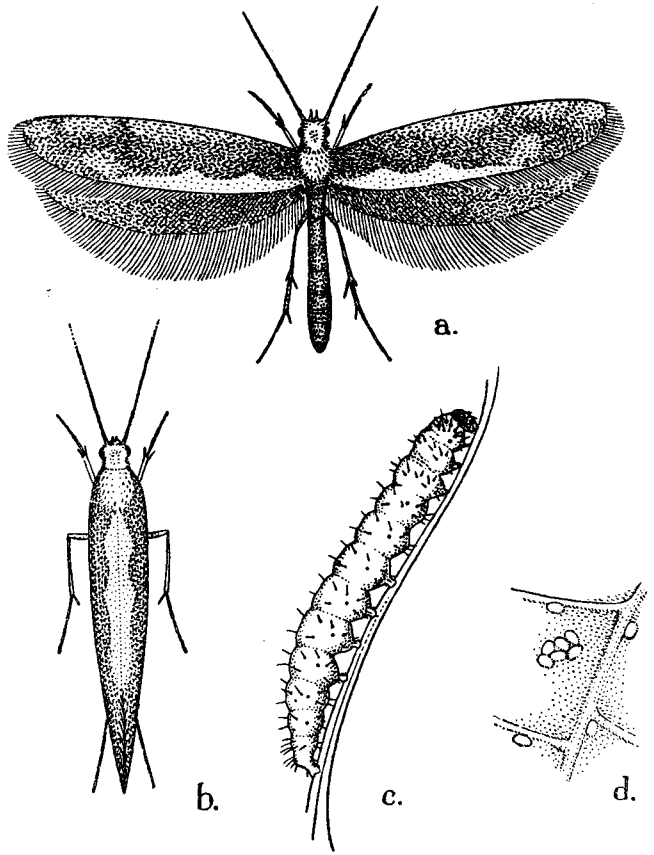

Fig. 1. *Plutella maculipennis*, Curt.: *a*, adult; *b*, adult in resting position; *c*, larva; *d*, eggs.

While this is possible to some extent for the meagre indigenous population, the observations of the writer do not support this view that this so-called first generation has any bearing on the " infestations " as, in the areas examined by him, the weeds were free from *Plutella* and yet a few days later the cultivated crops were swarming with moths. For this reason the infestations studied in Thanet and Northumberland during July and August have been termed the " first generation," there being no evidence to the contrary.

3. Practical Work.

(a). *Choice of Parasites for Introduction.*

Before any practical work was attempted the references to *Plutella maculipennis* in literature were consulted and the following formidable list of recorded parasites was obtained :—

ICHNEUMONOIDEA.

Angitia armilata, Grav.
Angitia cerophaga, Grav.*
Angitia chrysosticta, Gmel.
Angitia fenestralis, Hlmgr.*
Angitia gracilis, Grav.
Angitia lateralis, Grav.
Angitia majalis, Grav.
Angitia nana, Grav.
Angitia plutellae, Vier.
Angitia tibialis, Grav.
Apanteles fuliginosus, Wesm.
Apanteles plutellae, Kurd.
Apanteles ruficornis, Hal.
Apanteles rufipes, Hal.
Apanteles sodalis, Hal.
Apanteles vitripennis, Hal.
Campoplex paniscus, Grav.
Chelonus blackburni, Cam.
Colastes varicolor, Wesm.
Diadromus subtilicornis, Grav.*
Diadromus varicolor, Wesm.
Eulimneria polynesialis, Cam.
Eulimneria paniscus, Grav.
Exochus erythronotus, Grav.
Limnerium fibrator, Cress.
Limnerium leontiniae, Brèth.
Limnerium parvum, Prov.
Limnerium tibiator, Cress.
Mesochorus velox, Hlmgr.
Meteorus spp.
Microplitis plutellae, Mues.
Omorga borealis, Zett.
Omorga cerophaga, Grav.
Phaeogenes discus, Cress.
Phaeogenes plutellae, Kurd.
Phygadeuon rusticellae, Brid.
Pimpla alternans, Grav.
Sagaritis latrator, Grav.
Tameleucha plutellae, Ashm.
Thyraeella collaris, Grav.

CHALCIDOIDEA.

Brachymeria spp.
Tumidcoxella plutellophaga, Gir.
Tetrastichus sokolowski, Kurd.

Of these parasites many proved to be duplicated by synonymy, while others were certainly errors or extremely rare occurrences. A few (those marked *) were found to be associated with *Plutella* in many different parts of the world, and the *Angitia* species appeared to be not only the most common in occurrence, but also the most significant numerically.

A preliminary survey in 1935 had shown that *Angitia cerophaga* and *Angitia fenestralis* appeared to be the most widespread and efficient parasites in England, and initial efforts were devoted to the provision of a sufficient supply of these two species for export, while the control of the Diamond-back Moth was being investigated as a whole.

(b). *Field Collection of Plutella maculipennis.*

There are three areas in England which seem to be most prone to Diamond-back Moth infestations ; these are the North-East Coast, the Isle of Thanet, and certain

parts of Wales. With the help of the Ministry of Agriculture, a close watch was kept on these districts, beginning with a general survey of the ground as early as 12th May, when no adults or overwintering pupae were discovered, either in the fields of the 1935 infestations or on weeds in their vicinity.

Although captures of single adult moths were made in various districts throughout the country during May and early June (Ministry of Agriculture Advisory Entomologists and Dr. C. B. Williams) it was not until 23rd June that the adults were seen in large numbers, simultaneously in Kent and in Wales. News was later received that in the latter area no infestation of larvae resulted.

On 14th June the writer began an inspection of Kent, and in the immediate vicinity of Wye, on Wye College Farm, a few small *Plutella* larvae were discovered, together with numerous adults of *Angitia fenestralis*, some of which were captured and sent to the laboratory for breeding purposes. On surveying Thanet it was discovered that the reported swarm of moths had resulted in some promising local infestations, especially at Sarre, where the fodder-kale fields contained numerous larvae, although the broccoli crop of the district was much cleaner.

Because of the extreme activity of the *Plutella* caterpillars no collection could be made at this stage, and it was necessary to wait until 22nd July, when the oldest larvae began to form their cocoons on the leaves.

As the pupation period may last only 10–12 days in hot weather, speed is essential for the collection of large numbers, and it was necessary to engage local labour by the help of which a total of over 25,000 cocoons was amassed in ten days. The collection was then abandoned because of the increasing emergence of both moths and parasites from the cocoons.

All the cocoons were picked by hand, the field workers tearing off small pieces of the plant to which the cocoons were attached and placing them in tins. This material was spread out on the floor of a warm dry room to enable newly spun cocoons to harden, and a special worker then removed each cocoon from its portion of leaf by means of forceps.

At the finish of the work in Kent, a visit was made to Bedfordshire, where the Diamond-back Moth had been reported, but although larvae and cocoons were seen, chiefly on kale and mangolds, in no place were there such numbers that a collection could have been made.

On 18th August the search of the North-East area was commenced, but although earlier reports had been promising, the severe summer had quashed incipient infestations and at only one place, Cockle Experimental Farm, Morpeth, were cocoons discovered in any numbers and a small collection of 3,000 made.

Later in the year Thanet was twice revisited in the hope that a second generation of the moth would develop, but the extraordinarily high parasitism of the first generation, coupled with the general rain and cold had crushed the infestation completely and only sample collections could be made.

Dissections of samples had been made continuously throughout the work and it was ascertained that over 80 per cent. of the material was parasitized by *Angitia cerophaga* and *Angitia fenestralis*. Of the total collected, 25,410 were dispatched to New Zealand, together with suggestions concerning the handling of the material, and from these over 10,000 adult *Angitia* were received alive. Approximately 3,000 were retained for study.

(c). *Breeding of Angitia cerophaga and Angitia fenestralis.*

Although the usual policy of Farnham House Laboratory is to avoid the mass breeding of parasites whenever field collections can be made, the scarcity and smallness of the *Plutella* infestations in England rendered necessary the breeding of large numbers of *Angitia cerophaga* and *Angitia fenestralis* to ensure sufficient material with which to form the nucleus of a colony in New Zealand.

It was therefore necessary to devise some technique by which the life of the parasites could be prolonged over five weeks. Table I summarizes a series of experiments on the viability of *Angitia* at a temperature of 4°C.

It will be seen that 42 days at 4°C. resulted in the death of all stages, with the exception of the pupal, in which a mortality of 50 per cent. was obtained. Twenty-eight days at this temperature was also fatal to the adults, but only a small mortality was incurred by the pupae.

It was therefore decided to adopt the following procedure on the voyage: The *Angitia* pupae were held at 4°C. for 28 days and then removed to a warmer temperature of approximately 15°C. At this latter temperature the adults emerged, but as they were provided with food they survived a further three weeks. Thus the total length of life was seven weeks, of which five were consumed in the voyage, leaving the ample amount of two weeks for liberation in the field or breeding in the laboratory.

The practical details of the packing, etc., for the shipment were as follows: As the parasite cocoons were taken from the cages they were placed in the refrigerator at 0°C. until the time for shipment arrived; they were then divided up into batches of 500 and each batch confined in a small cage formed by nailing a piece of copper gauze, suitably cut and bent, on the underside of the lid closing a wooden box of size 4 in. × 5 in. × 12 in. (Plate IX, fig. 2).

The gauze, of mesh twelve strands per inch, retained the cocoons but permitted emergent adults to pass through into the general space of the box; this method of segregating the adults, so that danger of entanglement by loose cocoons is eliminated, was communicated to the writer by Mr. W. F. Sellers, of the United States Bureau of Entomology and Plant Quarantine, and it has proved to be an excellent way of shipping parasites which may emerge on the voyage.

The consignments of the wooden boxes were despatched in the vegetable chill-room of the vessels at about 4°C., but because prolonged refrigeration kills the parasites the boxes were removed from the chill-room after the duration of one month and placed at a temperature of approximately 15°C., at which temperature the adults emerged after a week and were received in this state by the Dominion Entomologist. Reports have been received that approximately 50 per cent. of the material arrived in good condition, and of those parasites which were dead on arrival, the short-lived males preponderated to a large extent.

4. Biology and Inter-relation of the Parasites in England.

(a). *List of the Parasites of Plutella maculipennis in England.*

In the course of the work it became evident that old records of parasites from *Plutella maculipennis* were often unreliable, and the following list is based upon those parasites which have been reared or inspected by the writer from several thousand specimens obtained from different parts of the country. In cases where only one or two specimens have been obtained, the British Museum is unwilling to give a specific name to the insect.

HYMENOPTERA.

ICHNEUMONIDAE.

ICHNEUMONINAE.		Stage of host attacked.
Phaeogenini:	*Phaeogenes* spp.	Pupa.
	Thyraeella collaris, Grav.	Pupa.

		Stage of host attacked.
Cryptinae.		
Phygadeuonini :	*Panargyrops* (*Leptocryptus*) *lamina*, Thom.	Hyperparasites on on larval parasites.
Hemitelini :	*Hemiteles areator*, Panz.	
	Hemiteles spp.	
Pezomachini :	*Gelis* spp.	
Pimplinae.		
Pimplini :	*Itoplectis maculator*, Fab.	Pupa.
	Itoplectis alternans, Grav.	Hyperparasite.
Ophioninae.		
Mesochorini :	*Mesochorus pectoralis*, Ratz.	Hyperparasite of larval parasite.
Campoplegini :	*Angitia cerophaga*, Grav.	Larva.
	Angitia fenestralis, Hlmgr.	Larva.
Braconidae.		
Areolinae.		
Microgasterini :	*Apanteles sicarius*, Marsh.	Larva.
Chalcididae.		
Pteromalinae.		
Rhaphitelides :	*Habrocytus* spp.	Hyperparasite.
Eulophinae.		
Eulophini :	*Eulophus* spp.	Hyperparasite.

(b). *Angitia cerophaga*, Grav. *and Angitia fenestralis*, Hlmgr.

These two parasites have a marked similarity in habit and morphology and it is often difficult to assign an individual to either species. Formerly they have often been recorded from many countries as a single species, completely as *A. cerophaga*, completely *A. fenestralis*, or else under various names such as *A. plutellae* and *A. gracilis*; further confusion has arisen from wrong synonymy and homology (Torka, 1929) and also by records of *Angitia* species from *Plutella* which are improbable or very unusual, *e.g. Angitia nana* (Morley *et al.*, 1933).

While the diagnostic differences (*vide* Key to Parasites) between *A. cerophaga* and *A. fenestralis* serve to place the majority of specimens into one or other of the two species (Boyd, 1934), an examination of a series composed of over a thousand individuals showed that these characters varied to such an extent that all stages of intermediate forms could be found. Some of these possess the wing type of *fenestralis* whilst the other characters are those of *cerophaga*. Although it is well known that the diagnostic characters of many of the Campoplegines are subject to variation, the extreme convergence exhibited by the two species suggests that a certain amount of inter-breeding may take place; this hypothesis is supported by the work of D. C. Lloyd, who succeeded in mating a pure strain of *A. fenestralis* male with a pure strain *A. cerophaga* female, and produced an F.1 generation showing mixed characteristics of both species and similar to some forms found in the field.

Should such relatively occasional hybrids be produced normally, their chance of mating with the greatly preponderating normal *A. cerophaga* or *A. fenestralis* is so large that it may be assumed that there is an immediate reversion to type, and that this F.1 series will keep a constant low proportion in the population as long as it exists side by side with the normal parent stock and there is no selecting factor operating for its benefit.

(b) Hosts of *Angitia fenestralis* :—

Adaina microdactyla, Hb.
Aristotelia tetragonella, St.
Callophrys rubi, L.
Ceuthorrhynchus quadridens, Panz.
Choreutis myllerana, Fab.
Clysia ambiguella, Hb.
Cnephasia wahlbomiana, L.
Coleophora pyrrhalipennella, Zell.
Depressaria hypericella, Hb.
Enarmonia diniana, Gn.
Hemerophila pariana, Cl.
Hypercallia christierana, L.
Hyponomeuta spp.
Hyponomeuta malinella, Zell.
Hyponomeuta padella, L.
Lita obsoletella, L.
Loxostege sticticalis, L.
Notarcha ruralis, Scop.
Phthorimaea operculella, How.
Polychrosis botrana, Schiff.
Polychrosis fuligana, How.
Simaethis fabriciana, L.
Spargonothis pilleriana, Schiff.
Tortrix costana, Fab.

The selection of possible alternate hosts for the very polyphagous *Angitia fenestralis* is not difficult, even in Thanet, where the character of the fauna is somewhat restricted. *Cnephasia* is perhaps the most likely species in which the parasite overwinters, for this Tortricid, unlike *Plutella*, passes the winter as a small larva, and perhaps it is this host stage which is necessary for the hibernation of *Angitia*. Furthermore, Dr. O. W. Richards has observed that the parasites emerging from the completed *Cnephasia* generation migrate to *Plutella maculipennis*, should that insect be present in the area.

In the case of *Angitia cerophaga* the problem is more difficult ; there are comparatively few recorded hosts of this insect and none of them is likely to be common in Thanet. However, the species attacked by the Campoplegines are not very well known and it is probable that future work will reveal that an alternate host exists.

(c). *The Hyperparasites of Angitia cerophaga and Angitia fenestralis.*

From the 25,000 *Angitia* cocoons which were examined in the course of the work during 1935 and 1936, the following hyperparasites were obtained :—

Hyperparasite	District of occurrence
Mesochorus pectoralis, Ratz.	Northumberland. Thanet.
Itoplectis alternans, Grav....	Northumberland. Thanet.
Leptocryptus lamina, Thom.	Northumberland. Thanet.
Hemiteles areator, Panz. ...	Northumberland.
Hemiteles spp.	Northumberland.
Habrocytus spp.	Northumberland. Thanet.
Eulophus spp.	Thanet.

Although the exposed position of the *Angitia* cocoons would appear to make them ideal objectives for hyperparasites, the actual number of such secondaries was very small, and only in the case of *Mesochorus pectoralis* did the parasitism by any one species rise above 0·1 per cent.

Mesochorus pectoralis occurred in both districts examined in 1936, but whereas a parasitism figure of only 1·5 per cent. was reached in Northumberland, in Thanet

(e). *Primary Parasites of Minor Importance.*

Itoplectis maculator, Fab., *Thyraeella collaris*, Grav., and *Phaeogenes* spp., were all bred from *Plutella* in 1935 and 1936, but only a few specimens were obtained of each (less than 0·1 per cent.) and, though the two former are constantly associated with the Diamond-back Moth in records throughout the world, there can be no doubt that they are not important in England.

Itoplectis maculator, a pupal parasite, is of especial interest because it is rarely recorded as a hyperparasite in spite of its polyphagous habits, and the specimens reared by the author from *Plutella* were undoubtedly primary. In an effort to provide this parasite for New Zealand, as a complement to the larval parasite *Angitia*, the author made a collection of *Tortrix viridana*, L., from which about 20 female *Itoplectis* were obtained, and then endeavoured to breed these fertilized females on pupae of *Plutella*. Although the Pimplines at times pierced the Lepidopterous pupae to such an extent that these were killed, no eggs were ever laid and the experiment was unsuccessful. In view of the disparity in size between the *Itoplectis* reared from *Tortrix* and any that could have developed from the small *Plutella* pupae, it would not be surprising if two biological races are involved and that each of these keeps to its own hosts, living in the widely separated environments of the cabbage field and the forest.

Little is known of the Diadromid, *Thyraeella collaris*, beyond that it has been recorded as a parasite of *Plutella* from many European countries, and still less is known of the *Phaeogenes*, the only two specimens of which have been reared by Dr. O. W. Richards, none being found in the 30,000 cocoons which have passed before the writer's observation.

(*f*). *The Inter-relation of the Parasites.*

This complex question cannot be treated in detail at present, but a few obvious points may be noted. *Angitia cerophaga*, *A. fenestralis*, and *Apanteles sicarius*, apparently enter the host at about the same stage. If the first two species occur together it is probably a matter of chance which is the survivor, as the larvae are essentially similar and the breeding work has shown no obvious superiority of one species. Analysis of samples in the field has shown that the individual populations of the two *Angitia* vary with the age of the infestation, and, to a certain extent, competition is avoided, although there must be a phase when the two species are in equal proportions; this condition, which is probably due to different times of emergence of *A. cerophaga* and *A. fenestralis* from their alternative hosts, ensured a high *Plutella* parasitism over a longer period than if only one species was involved. It is not known what happens in the rare cases when *Angitia* spp. and *Apanteles sicarius* occur together in the same host. If the two parasites do not interfere with each other's development in the early stages, it is probable that the *Apanteles*, which enters on its active feeding stage earlier than *Angitia*, will succeed in completing its development and, after its emergence from the caterpillar, the *Angitia* must inevitably perish.

The remaining primary parasites are so scarce that speculation on the part they play in the complex would be unprofitable. However, it is obvious that the tremendous reduction in hosts surviving to pupate, produced by the parasites of the larvae, must have an adverse effect on the pupal parasites *Itoplectis maculator* and *Phaeogenes* spp. On the other hand, the fact that all the parasites attack other Lepidopterous hosts make them, to a large extent, independent for their reproduction on the supply of *Plutella maculipennis*.

(*g*). *Key to the Adult Parasites of Plutella maculipennis in England.*

The following key to the adult parasites of *Plutella maculipennis* in England has been compiled so that future workers may readily identify the parasites and hyperparasites which may be reared from this host. Where only one or two specimens of a

hyperparasite were obtained, the specific name could not be given with any certainty by the British Museum. The diagnostic characters for the separation of the *Angitia* are those formulated by Boyd (1934).

1. Wingless.....*Gelis* spp.
   Winged 2
2. Wings with rudimentary venation ; antennae elbowed.....3
   Wings with well developed venation ; antennae not elbowed.....4
3. Marginal nerve shorter than costa ; front tibia with large curved spine.....
   Habrocytus spp.
   Marginal nerve as long as or longer than costa ; front tibia with short, thin, straight spine.....*Eulophus* spp.
4. Wings with one recurrent nerve ; thorax shiny black ; wing venation well marked.....*Apanteles sicarius*, Marsh.
   Wings with two recurrent nerves.....5
5. Wings with three dusky transverse areas..... ...*Hemiteles areator*, Panz.
   Wings not so 6
6. Areolet five-sided ; sometimes outer side missing.....7
   Areolet four-sided.....10
7. Post-petiole narrow ; terebra at least one-quarter the length of the abdomen...8
   Post-petiole broadened ; terebra only just exserted.....9
8. Areolet complete.....*Panargyrops* (*Leptocryptus*) *lamina*, Thoms.
   Areolet with outer side missing.....*Hemiteles* spp.
9. Clypeus indistinctly separated from frons by a faint line ; sides of thorax red.....*Thyraeella collaris*, Grav.
   Clypeus distinctly separated from frons by a deep groove.....*Phaeogenes* spp.
10. Areolet large ; abdomen black or dark brown with a single broad yellow band
    Mesochorus pectoralis, Ratz.
    Areolet smaller ; abdomen entirely black or with several narrow yellow bands...11
11. Abdomen petiolate and laterally compressed.....12
    Abdomen sessile.....13
12. Recurrent nerve received beyond the centre of the areolet ; ovipositor sheaths about 0·85 mm. ; fore coxae mainly yellowish and pterostigma more or less darkened with dark margins.....*Angitia cerophaga*, Grav.
    Recurrent nerve received at or before centre of areolet ; ovipositor sheaths about 1·25 mm. ; fore coxae mainly black and pterostigma pale.....
    Angitia fenestralis, Hlmgr.
13. Hind trochanters black ; hair on thorax long.....*Itoplectis maculator*, F.
    Hind trochanters red ; hair on thorax short.....*Itoplectis alternans*, Grav.

5. The Natural Control of Plutella maculipennis.

As the word " control " may have several different meanings, it is necessary at the outset of this section to present certain definitions indicating the precise meaning of the terms which will be used.

Finally, I am much indebted to Mr. J. F. Perkins, of the British Museum, for the identification of the ICHNEUMONIDAE.

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