

The Pathogens of Diamondback Moth and Their Potential for its Control — a Review

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Abstract

The larvae and less frequently the pupae of *Plutella xylostella* (L) are sometimes attacked naturally by pathogens, particularly two fungi of the family Entomophthoraceae, *Erynia blunckii* and *Zoophthora radicans*. Other pathogens recorded include one other entomophthoraceous fungus, a granulosis virus, one or possibly two nucleopolyhedrosis viruses and *Bacillus thuringiensis* var *kurstaki*. In the laboratory, larvae were also susceptible to strains of several deuteromycete fungi, other nucleopolyhedrosis viruses and several varieties of *B. thuringiensis*. Of these pathogens, only *B. thuringiensis* is produced commercially and the derived products are used to control *P. xylostella* in the field. The bacterium, however, spreads inefficiently between host individuals and for effective control, as with chemical insecticides, repeated applications are necessary. Laboratory tests indicate that *E. blunckii*, *Z. radicans*, some of the deuteromycetes and certain viruses, all of which spread readily between individuals, may have potential as control agents. While none of these is produced commercially, methods for their mass cultivation are available though they need development. For each of these pathogens further laboratory and field trials are needed to select the most infective strains and to test application methods and formulations.

Introduction

The diamondback moth (DBM), *Plutella xylostella* (L) (Lepidoptera: Yponomeutidae), occurs throughout the world wherever crucifers are grown. Its recorded distribution has been mapped (CIE 1967). In many areas DBM causes little damage, probably because its numbers are held in check by natural enemies (Hardy 1938). In the UK the insect is widespread but causes only sporadic damage chiefly in the east. The most recent outbreak of the pest in the UK, in 1958, resulted from easterly winds bringing vast numbers of the moths from countries bordering the east shores of the Baltic Sea, across the North Sea (French and White 1960). Serious damage was limited by chemical pesticides, chiefly DDT. In some parts of the world, however, notably in the Far East, DBM causes damage regularly and repeated applications of insecticides are required for its control. As a result, resistance has developed to many of the previously suitable compounds (Sudderuddin and Kok 1978). This, coupled with an increased awareness of the environmental consequences of excessive pesticide use, encourages further interest in non-chemical methods of control including the use of pathogenic microorganisms and viruses.

This paper describes the pathogens that attack DBM in nature, reviews the results of laboratory and field trials in which the insect has been challenged by these and a range of other pathogens and considers the prospects for the microbial control of this pest.

Pathogens Naturally Attacking DBM

The ecology of DBM, including the effects of natural enemies, has been studied in a number of countries. It is clear that the moth has become adapted to many diverse environments and the time scale of different stages in its lifecycle has been modified accordingly. Nevertheless records of pathogens are consistently restricted to those affecting the larvae and rarely the pupae. Most references are to infection by fungi of the family Entomophthoraceae though there are a few records of virus infections and one of infection by the bacterium *Bacillus thuringiensis* Berliner (Table 1).

Table 1. Records of pathogens of DBM

Pathogen	Country	Reference
<i>Viruses</i>		
granulosis	Japan	Asayama and Osaki (1970)
multiple-embedded nucleopolyhedrosis	Japan	Zeya (1968) according to Biever and Andrews (1984)
nucleopolyhedrosis	?	Varma and Gill (1977)
<i>Fungi</i>		
<i>Zoophthora radicans</i>	New Zealand South Africa	Robertson (1939), Kelsey (1965) Ullyett and Schonken (1940), Ullyett (1947)
	Finland	Kanervo (1946, 1949)
	Chile	Aruta et al (1974)
	Malaysia	Ooi (1979, 1981)
	Philippines	Velasco (1983)
	Japan	Yamamoto and Aoki (1983)
<i>Erynia blunckii</i>	Germany	Lakon (1935), Zimmermann (1978)
	Finland	Kanervo (1946)
	USSR	Woronina (1971) according to Zimmermann (1978)
	Japan	Tomiyama and Aoki (1982)
<i>Erynia</i> sp. probably <i>virescens</i>	Finland	Kanervo (1946)
<i>Bacteria</i>		
<i>Bacillus thuringiensis</i> var. <i>kurstaki</i>	Yugoslavia	Purrini (1977), Vankova and Purrini (1979)

Viruses

Asayama and Osaki (1970) recorded many DBM larvae infected with a granulosis virus (GV) in a cabbage plantation in Aichi Prefecture, Japan in May 1968. The color of the larvae at an advanced stage of infection changed to pale yellow from the normal dull green. After death they turned dark brown and swelled. A white fluid was often discharged from the integument. The capsules of this GV were uniformly ovo-cylindrical, $411 \pm 17 \times 240 \pm 13 \text{ m}\mu$ and the rod-snaped virus particles were $260 \text{ to } 280 \times 40 \text{ to } 45 \text{ m}\mu$. The structure of the virus and its effect on host tissues are described in a series of articles published in Japanese (Asayama and Inagaki 1975a, 1975b; Asayama 1975a, 1975b, 1976).

Biever and Andrews (1984) studied the susceptibility of some lepidopterous larvae to a multiple-embedded nucleopolyhedrosis virus (NPV) isolated in Oxford, UK by A. Zeya, from DBM originating in Japan. No details are given of the degree of mortality caused in the larval population.

An NPV isolated from DBM was also used in experiments described by Varma and Gill (1977). No details of its origin are given except that it was supplied by T. Sunkaran of the Commonwealth Institute for Biological Control, Bangalore, India, and no description of the infected host or of the virus is provided. It is not known whether this virus corresponds to that studied by Bieber and Andrews (1984).

Fungi

Zoophthora radicans (Brefeld) (= *Entomophthora sphaerosperma*) (Phycomycetes: Entomophthoraceae) infects insects from several orders and is a widespread pathogen of DBM (Table 1) attacking usually the larvae but also sometimes the pupae (Robertson 1939, Kanervo 1945). Larvae killed by this fungus are attached to the substrate by strong rhizoids emerging along the ventral surface of the abdomen. The fungus may then form a mat of conidiophores that extends over the larvae and beyond its margins so that the detailed shape of the host is no longer recognizable (figured in Ullyett and Schonken 1940, Kanervo 1946, Ullyett 1947). The primary conidia develop from these conidiophores and are violently discharged to a distance of a few millimeters, forming a halo around the dead larvae. The conidia (Figure 1) are uninucleate and elliptical with a rounded apex and roundly conical base demarcated from the body of the conidium by a slight 'collar' marking the ring of attachment to the conidiophore. The conidia range in size from 15×5 to 26×8 . Secondary conidia, developing directly from the primary ones, are of two types: either they resemble the primary ones or they are capilloconidia formed on a slender capillary tube arising from the primary conidium. The capilloconidia (Figure 1) are fusiform, tapering to base and apex and have dimensions of 13×5 to 25×8 μ .

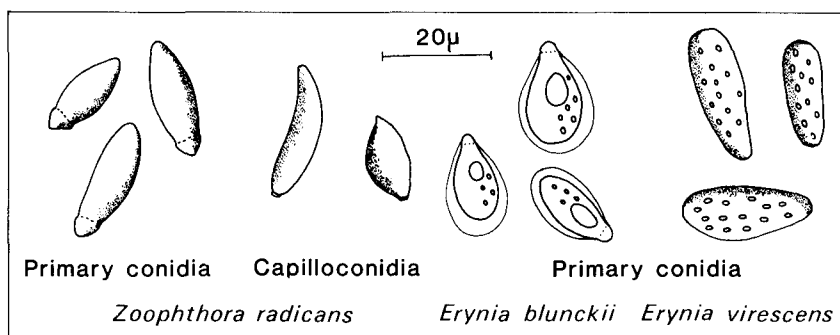


Figure 1. Conidia of entomophthoraceous fungi recorded from DBM

In some larvae, instead of conidiophores, thick-walled spherical resting spores (about 24 to 28 μ diam.) develop within the body of the infected host. On death such larvae shrivel slightly, darken in color and remain firm when touched with a needle.

Z. radicans periodically causes high mortality in DBM populations in most of the countries where the fungus has been recorded (Table 1). Kelsey (1965) found that under natural conditions in New Zealand the fungus almost eliminated a population of larvae in only 10 days. Usually the same effect was noted only after about 30 days. However, following detailed surveys in England, Hardy (1938) concluded that it is rare to find caterpillars dying from any species of fungus in this country. Further, there are no references to DBM infection by *Z. radicans* in the rest of Europe nor in North America, even though it is a frequent pathogen of many other hosts, including Lepidoptera, in these regions.

Robertson (1939) considered that the most important factors governing the mortality caused by the fungus are moisture and a high density of the host. Epizootics can be expected when these conditions coincide. To this should be added that a strain of the fungus infective for DBM must also be present, and in some regions as in England where the pest occurs infrequently there is little opportunity for the fungus to persist from one outbreak population to the next. This may explain why the fungus is not recorded more frequently from England and most of Europe.

Ullyett and Schonken (1940) showed that in South Africa the natural control of DBM provided by *Z. radicans* was sometimes so complete that hymenopterous parasitoids of the pest, which normally have an important regulatory effect on numbers, were eliminated through the absence of their host. When the fungus subsequently disappeared, the pest population developed more quickly than that of the parasitoid and caused more damage than it had before the intervention of the fungus. Kelsey (1965) also recognised this occurrence but considered, nevertheless, that in programs of biological control the advantages of introducing *Z. radicans* outweighed the disadvantages.

DBM is the only known host of another entomophthoraceous fungus, *Erynia blunckii* (Lakon). This fungus has been recorded from fewer countries (Table 1) and less frequently than *Z. radicans*. Larvae killed by *E. blunckii* are fixed to the substrate by rhizoids and become covered in a felt-like mat of conidiophores (figured by Zimmermann 1978) similar to that formed by *Z. radicans*. Pseudocystidia, sterile fungal processes, extend far beyond the tips of the conidiophores, and the conidia are discharged in vast numbers forming a heavy deposit around the dead host. The conidia are morphologically distinct from those of *Z. radicans* (Figure 1). They are uninucleate, pyriform and range from 13 x 7 to 20 x 11 μ . In water and in other liquids the outer membrane of the wall often separates from the inner one so that the conidium appears to be contained in a bubble from which only the basal papilla protrudes. As in the conidia of *Z. radicans*, the line of attachment to the conidiophore is marked by a faint collar. Secondary conidia resemble the primary ones and capilloconidia are not formed. Resting spores of *E. blunckii* have not been found.

Tomiyama and Aoki (1982) recorded an epizootic caused by this species in a radish field near Tokyo, Japan; but no details are given in this or any other publication of the degree of mortality caused or the conditions in which outbreaks of infection occur.

The only other pathogenic fungus from DBM was recorded in Finland and identified tentatively as *Entomophthora virescens* Thaxter (= *Erynia virescens* (Thaxter) (Phycomycetes: Entomophthoraceae) by Kanervo (1946). This species was originally described from larvae of an *Agrotis* species (Lepidoptera: Noctuidae) by Thaxter (1888) in North America. The conidia (Figure 1), according to Kanervo (1946) range in size from 18 x 11 to 30 x 15 μ . They are irregular in shape, ovoid to pyriform with a rounded apex and base. There are no details of the effect of this fungus on populations of DBM nor of the conditions which favor its spread.

Bacteria

The only pathogenic bacterium recorded from DBM is *B. thuringiensis* var *kurstaki*. Purrini (1977) and Vankova and Purrini (1979) discovered DBM larvae infected with this bacterium apparently in old watermills in Yugoslavia but it is not clear what the larvae were feeding on. Infected larvae of stored product moth pests, much more usual hosts for *B. thuringiensis* than phytophagous larvae, were found at the same time and were probably the primary hosts.

B. thuringiensis is a spore-forming bacterium characterized by the production of a protein crystal comprising the so-called delta endotoxin, which is toxic for larvae of Lepidoptera and the aquatic larvae of certain Diptera including mosquitoes and black

flies, but harmless to all other organisms including man. Currently, 19 serotypes of this organism, distinguished by their flagellar or H-antigens, have been characterized and some of these serotypes have been further divided into biotypes. Some isolates of several serotypes produce, in addition to the crystal endotoxin, the beta exotoxin which has a wider spectrum of toxicity and is slightly harmful to birds. Certain isolates of *B. thuringiensis* are produced commercially but those producing the exotoxin are not permitted for most pest control purposes.

Larvae become infected with *B. thuringiensis* by ingesting the bacteria from cadavers or the faeces of infected insects. The endotoxin paralyzes the gut, causing feeding to cease, and lowers the pH. In these conditions the bacterium multiplies, sporulates, breaks down the gut wall and enters the haemocoel causing a lethal septicaemia.

Experimental Infections

Several of the pathogens described in the previous section have been tested in the laboratory for their infectivity for DBM and others, not associated naturally with this host, but which may have a similar or even greater potential for use as control agents, have also been tested (Table 2).

Table 2. Pathogens infective for DBM in experimental tests

Pathogens	Reference
<i>Viruses</i>	
Multiple embedded nucleopolyhedrosis (from DBM)	Biever and Andrews (1984)
Polyhedrosis (from DBM)	Varma and Gill (1977)
Multiple embedded nucleopolyhedrosis (from <i>Autographa californica</i>)	Vail et al (1972), Vail and Jay (1973), Burgerjon (1977)
Multiple embedded nucleopolyhedrosis (from <i>Galleria mellonella</i>)	Burgerjon (1977)
<i>Chilo</i> iridescent virus	Ohba (1975)
Granulosis virus (from DBM)	Asayama references
<i>Fungi</i>	
<i>Beauveria bassiana</i>	Fargues et al (1979, 1983), Ignoffo et al (1979), Robert and Marchal (1980)
<i>B. brongnartii</i>	Fargues et al (1979), Robert and Marchal (1980)
<i>Metarhizium anisopliae</i>	Robert and Marchal (1980)
<i>Paecilomyces fumoso-roseus</i>	Robert and Marchal (1980)
<i>Erynia blunckii</i>	Tomiyama and Aoki (1982)
<i>Zoophthora radicans</i>	Ulliyett and Schonken (1940), Wilding and Mardell (unpublished)

Viruses

Vail et al (1972) tested an NPV isolated from *Autographa californica* (Speyer) (Lepidoptera: Noctuidae) for control of *Trichoplusia ni* (Hubner) (Lepidoptera: Noctuidae) in the field and from one plot recovered subsequently a DBM larva infected with NPV. Laboratory tests with this virus confirmed that it was infective for DBM when fed at a dose of 10^4 polyhedral inclusion bodies (PIB)/mm² of diet surface (Vail et al 1970). The virus from DBM was then tested against *T. ni* by feeding 2.4×10^3 PIBs/mm² and the results confirmed the cross infectivity of the virus. The symptoma-

tology of the infection of DBM larvae and several other Lepidoptera by the same virus isolate was reported by Vail and Jay (1973). DBM larvae died three to four days after ingesting the virus. Infected larvae became swollen and flaccid and the integument became shiny before disintegrating.

Burgerjon (1977) tested two serologically and morphologically indistinguishable isolates of NPV for their infectivity for a number of lepidopterous larvae including DBM. One isolate was that from *A. californica*, considered above, and the other was isolated in the USSR from *Galleria mellonella* (Linnaeus) (Lepidoptera: Pyralidae). The larvae were inoculated by spraying an aqueous suspension to the surface of the cabbage leaves on which they were fed. The *G. mellonella* isolate was slightly more infective than the *A. californica* one but even a dose of 4×10^4 PIBs/mm² of leaf surface killed only about 86% of the test larvae. Further, the same virus isolates were much more infective for certain other host species.

Another NPV, isolated from DBM by A. Zeya (Table 1), also had a high LC₅₀ (1.5×10^4 PIBs/mm² of diet surface for 3rd instar larvae) (Biever and Andrews 1984). This contrasts with LC₅₀s of less than 1 PIB/mm² for *T. ni* and *Spodoptera ornithogalli* (Guenee) (Lepidoptera: Noctuidae) with the same virus. The authors concluded that DBM was not the natural host for this virus.

An NPV described as a 'nuclear polyhedrosis virus of *Plutella*' was applied as one treatment in an experiment comparing its efficacy with that of four *B. thuringiensis* preparations for DBM control (Varma and Gill 1980). The suspension of the virus was prepared by homogenizing one cadaver, presumably of DBM, in distilled water, filtering through cheesecloth and making the volume up to one liter with water. The leaves of the plants were sprayed, using an atomizer, at 15-17 ml/plant and the treated plants were kept in screened cages. The virus produced 42% mortality after seven days.

Larvae of DBM were among 65 species of Lepidoptera to become infected with *Chilo* iridescent virus after per os inoculation but details of the dosage and mortality are not given (Ohba 1975).

In studies on the histopathology of the infection of DBM by granulosis virus, Asayama and his co-workers (Asayama 1975a, 1975b, 1976, Asayama and Inagaki 1975a, 1975b, Asayama and Osaki 1970) infected larvae experimentally but give no details of the dose applied or the degree of mortality caused. This virus was non-infective per os for *Pieris rapae* (L) (Lepidoptera: Pieridae), *Bombyx mori* (L) (Lepidoptera: Bombycidae) and four noctuid species (Asayama and Osaki 1970).

Fungi

Ullyett and Schonken (1940) infected DBM larvae with *Z. radicans* by applying a suspension of the conidia from an *in vitro* culture to the cuticle of the larvae with a wet brush. No figures for the success of this method are given but the authors state that the results were better than those obtained with the method described by Sawyer (1933) who enclosed larvae of *Rhopobota naevana* (Hubner) (Lepidoptera: Tortricidae) in vessels plugged with potato slices on which the fungus was growing. They also stated that they were unable to obtain infection with any degree of certainty with either method.

We have begun to develop a method for infecting DBM larvae with *Z. radicans* (Wilding and Mardell, unpublished). Third to 4th instar larvae were exposed to spore showers from 2 cm diam discs cut from *in vitro* cultures on agar medium of a strain (NW 33 = No. 633, Collection of G. Remaudiere, Institut Pasteur, Paris) isolated from *Tortrix viridana* (Linnaeus) (Lepidoptera: Tortricidae) in France in 1975 and stored subsequently in liquid nitrogen. The larvae were exposed to the shower of conidia for three hours and then kept in a moist box for a further 24 h. No attempt in this preliminary experiment was made to assess the dose of conidia applied. In two replicate tests four

and seven individuals became infected out of 20 inoculated in each. A few larvae also became infected after confinement with a deposit of conidia from the same fungus. The results of these experiments using a culture isolated many years ago from a heterologous host suggest that the techniques used are suitable for development.

In their studies on the histopathology of *E. blunckii* on DBM, Tomiyama and Aoki (1982) infected larvae using a similar technique to that we employed with *Z. radicans*. The larvae were confined for 24 h in a cage while exposed to a shower of conidia from cultures of the fungus on agar discs. No information is given about the dose administered or the mortality that resulted.

Robert and Marchal (1980) compared the infectivity of a number of entomogenous hyphomycetes for larvae of DBM to determine whether this insect was a suitable target host for screening such fungi. Both surfaces of 50 mm diam leaf discs were sprayed with a suspension of the spores and placed in a box containing 20 3rd instar newly molted larvae in an atmosphere kept moist for 48 h. These fungi invade the larvae through the cuticle, not through the gut wall, and the purpose of treating the leaf discs was to ensure that the larvae made contact with the inoculum while they were eating.

The larvae were treated with two strains of *Beauveria bassiana* (Balsamo), two of *B. brongnartii* (Saccardo), five of *Metarhizium anisopliae* (Metschnikoff), one of *M. flavoviride* Gams and Roszypal, one of *Nomuraea rileyi* (Farlow) and one of *Paecilomyces fumoso-roseus* (Wize) all at 10^8 spores/ml (equivalent to 4×10^5 spores/cm² leaf surface). The mortality recorded after six days was significantly greater than that of the untreated larvae for all the *Beauveria* strains, two *M. anisopliae* strains and *P. fumoso-roseus*. Further trials gave LC₅₀ values, in spores/ml, of 2.2×10^7 for conidiospores of one strain of *B. brongnartii* and of 2.3×10^7 (unformulated), 7.5×10^6 (lyophilized) and 1.5×10^7 (clay-coated) for three blastospore formulations of a strain of *B. bassiana*.

The infectivity of lyophilized blastospores of *B. bassiana* for DBM was unimpaired after one month storage at 5°C and only slightly diminished after five months (Fargues et al 1979). Clay-coated blastospores were still infective for DBM after three weeks in soil whereas the unformulated spores lost most infectivity after only two weeks. This and associated findings led the authors to suggest that clay-coating may be a satisfactory way of formulating entomopathogenic hyphomycetes for field use.

Ignoffo et al (1979) tested the mycoinsecticide Boverin against DBM using a similar method to that of Robert and Marchal (1980). Boverin is a preparation of conidiospores of a strain of *B. bassiana* selected for its activity against Colorado beetle, *Leptinotarsa decemlineata* (Say) (Coleoptera: Chrysomelidae). The LC₅₀ for three-day old larvae of *P. xylostella* was 2.7×10^8 spores/ml (equivalent to 1.5×10^6 /cm² of leaf surface).

Bacteria

There have been several studies on the effects of *B. thuringiensis* varieties on DBM (Kreig and Langenbruch 1981) but only some of these will be discussed here.

Burgerjon and Biache (1967) compared the susceptibility of 24 species of Lepidoptera including DBM to seven strains of *B. thuringiensis* of serotypes H-1, H-3, H-4, H-5 and H-6. DBM was susceptible to each of the serotypes tested. The different strains were prepared in an identical way and formulated as a dry powder. For a given concentration of the powder in water, serotype H-6, var *subtoxicus* was most toxic. Serotype H-5, var *galleriae* contained many more viable spores per gram of powder yet it was slightly though non-significantly less toxic than var *subtoxicus*.

Commercial preparations of two of the serotypes examined above, Dipel (serotype H-3a/3b, var *kurstaki*) and Bactospeine (serotype H-1, var *thuringiensis*) were compared

for their toxicity to 3 day-old DBM larvae (Ooi 1981). Both were effective, with Dipel just 1.3 times as toxic as Bactospeine. Rautapaa (1967) recorded that another commercial product, Biotrol (serotype H-1, var *thuringiensis*), at 13×10^5 spores/cm² of leaf surface, killed larvae in two days. However, serotype H-14, var *israeliensis* now available commercially for black fly and mosquito control was non-toxic to DBM (de Barjac 1978).

In an attempt to produce strains with increased toxicity for pests and reduced toxicity for *B. mori*, Jangi and Ibrahim (1983) gamma-radiated a strain of serotype H-7, var *aizawa* isolated from the commercial preparation Bacillex. Some of the isolates obtained had diminished toxicity to *B. mori* but of more interest here is an up to six fold increase in toxicity to DBM of some isolates.

Certain pesticides and *B. thuringiensis* acted synergistically in killing DBM in combined treatments (Hamilton and Attia 1977). However, combinations of Dipel with two widely used organophosphorus insecticides, demeton-S-methyl and dimethoate, reduced the effectiveness of the *B. thuringiensis* preparation alone by 4 and 10 times respectively.

There is no evidence for any pest having developed resistance to the delta endotoxin of *B. thuringiensis* but resistance to the beta exotoxin has been induced in houseflies, *Musca domestica* (L) (Diptera: Muscidae) by exposing successive generations to the toxin in the laboratory (Harvey and Howell 1965). A strain of DBM held under high selection pressure from var *thuringiensis* for 10 generations failed to show a difference in susceptibility from the untreated strain (Devriendt and Martouret 1976).

Field Trials

Pathogens other than *B. thuringiensis* have rarely been field tested against DBM and the results of these few trials are mostly poorly documented.

Granulosis viruses isolated from *P. rapae* and DBM were sprayed on crucifer crops in Taiwan and reduced numbers of both pests (Wang and Rose 1978). Studies in 1974 and 1975 showed that the mortality caused by the DBM GV decreased from 97.6 to 6.5% as the duration of exposure to sunlight increased from 4 to 60 h (Kao and Rose 1976). Of several protectants tested, India ink protected the virus and prolonged its effectiveness best. The same virus has been field tested in Malaya but details of the results are not yet published (Kadir 1984).

According to Biever and Andrews (1984), an NPV of DBM from Japan has been used in Malaysia and India for the control of this pest. No field data are available and Biever and Andrews consider from their laboratory studies that DBM is not the natural host of this virus and that it would probably more effectively control larvae of other Lepidoptera.

Only Kelsey (1965) has described the application of a fungus for DBM control. Two fields of crucifer forage crops in New Zealand in each of two years were treated with a macerate of larvae infected with *Z. radicans*. The time taken to give adequate control was only reduced in fields where the fungus was not already present but even in such cases the author concluded cautiously that artificial introduction 'may have some merit'. However, only one application was necessary whereas when organophosphorus insecticides were used a second spray was sometimes needed to prevent reinfestation. Farmers were advised not to treat a crop with chemical insecticides when the fungus was present in the field.

Most of the work on the use of *B. thuringiensis* for DBM control has been done either in the US or in southeast Asia. In the US there is a complex of damaging

lepidopterous pests on crucifers, including *T. ni* and *P. rapae* as well as DBM. Consequently the success of various pesticides, either chemical or those based on *B. thuringiensis*, in protecting the crop, is as much a measure of their ability to control these other pests as it is that of DBM. Most publications, however, include figures for the reduction in numbers of each of the species. For example, Creighton and McFadden (1975) field tested three commercial preparations of *B. thuringiensis*, several chemical insecticides and combinations of the bacterial preparations with the chemicals, on cabbage crops in South Carolina. Each of the *B. thuringiensis* preparations, Dipel wettable powder, Bactospeine wettable powder, and Bactospeine 'flowable', applied weekly, significantly reduced numbers of DBM. Dipel was tested at a range of doses and gave reasonable control of DBM and *P. rapae* but not *T. ni*, at 0.7 kg/ha. A combination of Dipel and chlordimeform hydrochloride each at this concentration gave significantly better protection against the complex of lepidopterous larvae than either product applied independently.

Results from the same laboratory (Creighton et al 1981) also established that the protection of cabbage by *B. thuringiensis* from caterpillars differed according to the cabbage cultivar but whether this was caused by an interaction between the cultivar and the treatment or merely the result of differential tolerance to larval damage between cultivars, irrespective of treatment, is not made clear.

Libby and Chapman (1971) compared the effectiveness of different commercial preparations of *B. thuringiensis* for control of DBM, *P. rapae* and *T. ni* on cabbage crops and determined that weekly applications of Dipel at 1.12 kg/ha and Thuricide (var *kurstaki*) at 0.56 kg/ha gave low foliar damage ratings and very acceptable control. They were more effective per weight of formulation than the then commercial preparation of var *thuringiensis*, Biotrol.

Eckenrode et al (1981) noted that *B. thuringiensis* is one of the two most widely used products for control of caterpillars on sauerkraut cabbage in New York State. Because this crop is processed for the market, it can tolerate more peripheral feeding damage than a cabbage crop destined for the fresh market. Consequently insecticides are applied relatively infrequently. Nevertheless, *B. thuringiensis* appears to give reasonable control especially of DBM.

In southeast Asia, DBM is the principal lepidopterous pest on crucifers and its control can be considered in isolation. Ho and Ng (1970) compared the efficacy of Thuricide with that of chemical insecticides for control of DBM on cabbage crops in 1968 and 1969. In an initial trial in which the products were applied weekly, Thuricide (at a concentration in water expressed as 1/80 (volume/volume)) gave better protection than any of the 16 chemicals but yields were low because soil conditions were poor and other pests were numerous. In further experiments, applications of Thuricide, at 1/80 and 1/160 (volume/volume), at four day intervals reduced larval numbers more than when applied at seven day intervals but not sufficiently to affect yield. Similarly, mortality though not yield was increased by raising the concentration from 1/250 to 1/100. These experiments lacked untreated control plots so that larval numbers and yields in the absence of any control measures were not determined. The authors, however, stated that Thuricide gave effective control and that on good soils, yields exceeding 100 t/ha were easily obtainable. Only when such yields were produced was the cost of treatment justified.

In more recent work, the success of Thuricide in controlling DBM was confirmed (Mohamad et al 1979). Control was as effective as that provided by a range of chemical insecticides including bendiocarb, acephate, methamidiphos, and diflubenzuron. These authors have also shown that, in the laboratory, *B. thuringiensis* retains 50% of its effectiveness after five days on leaves of turnip (Mohamad et al 1980).

Discussion

This account has shown that many different pathogens are active against DBM but of these only *B. thuringiensis* has been adequately field tested and is used commercially. The currently available preparations of this bacterium based on serotype 3a/3b, var *kurstaki* are highly infective for this pest. However, field tests show that its activity begins to diminish after only a few hours in daylight. Further, it spreads inefficiently between host individuals. Consequently, like many chemical pesticides, it has to be applied repeatedly to ensure control. Its use is also limited in those regions of the world where DBM co-exists with other lepidopterous pests of crucifers against which *B. thuringiensis* is only partially successful. Nevertheless, because it is commercially available at a competitive price, this organism will continue to provide by far the greatest potential for the microbial control of DBM for several years to come. Further, current research on genetic improvement of *B. thuringiensis* should lead to the development of strains of the bacterium with a greater potency than those currently available.

A number of viruses infective for DBM have been described but only the GV discovered in Japan by Asayama and Osaki (1970) appears to have caused a high level of mortality in a field population of DBM. Experimental work with the other viruses isolated from the larvae indicates a rather low susceptibility suggesting that DBM is not the principal host. However, further intensive screening of these viruses and those from other hosts for their infectivity for DBM in the laboratory and field should be undertaken. Although none of these viruses are available commercially in quantities required for field use, the related NPV of *Heliothis* species (Lepidoptera: Noctuidae) is used for the control of caterpillars on cotton and the techniques required for the mass production and application of such viruses are therefore available (Ignoffo and Couch 1981).

Some fungi are highly infective for DBM and cause an important natural mortality. Others have proved infective in laboratory tests. However, none of them has been adequately field tested for control of DBM. Methods for the large-scale production of some of them, those of the Deuteromycetes, are available (Hall and Papierok 1982). One of these, *B. bassiana*, causes allergic reactions in sensitive people and is therefore unlikely to be developed for commercial use (Hussey and Tinsley 1981) but all the available evidence suggests that other fungi of potential are harmless to mammals. No species of Entomophthoraceae is produced commercially but methods for their production have been developed and research into the possibility of using them for control of aphids, delphacids and certain Lepidoptera is current (Wilding 1981, Latge 1982).

Z. radicans, the most important of the naturally occurring pathogens of DBM is relatively well researched. A US patent for its production has been applied for by Drs D. McCabe and R. S. Soper (R. S. Soper, Boyce Thompson Institute, USA, personal communication) and provisional attempts to use strains of this fungus for control of aphids in Australia (Milner et al 1982) and spruce budworm, *Choristoneura fumiferana* (Clemens) (Lepidoptera: Tortricidae) in the US (Soper 1982) have demonstrated that the fungus can be artificially introduced into insect populations and provide some control.

All fungi require a saturated or near-saturated atmosphere for the completion of those stages in their lifecycle that occur outside the host. Their effectiveness as control agents is therefore limited in dry conditions. The duration for which moist conditions must persist, however, differs according to the species and strain of fungus. Often, the microenvironment within the crop canopy remains moist for long enough each day, particularly during the night, to ensure the infection of the host. In many of the regions where DBM is a problem, for example the Cameron Highlands of Malaysia, the nights are cool and humid providing apparently suitable conditions for fungus spread.

A disadvantage of pathogens for pest control is that most, other than *B. thuringiensis* which paralyzes the gut wall and thereby prevents feeding soon after it

is ingested, allow their host to continue damaging the crop for several days before death. Consequently the timing of application is crucial and adequate forecasting of potential infestation highly important. Against this, the ability of most pathogens to persist and multiply in the host population should ensure that a single application is sufficient. This, coupled with the advantage that a microbial pesticide is unlikely to kill any of the natural enemies of the pest suggest that their use for the control of DBM should receive greatly increased attention.

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