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11 Orchard Applications

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11.1. Introduction

Orchards consist of perennial tree plantings that provide various agricultural products. A number of economically important pests occur in most types of orchards. Many orchards contain attributes, e.g. hosts available through much of the year, favourable soil conditions (moist, sandy) and shade, that are amenable to insect suppression using entomopathogenic nematodes (EPNs). Additionally, crops produced in orchards are often relatively high in value, which facilitates economic feasibility of nematode applications. As a result, a number of orchard pests have been extensively studied for their potential to be controlled by EPNs, and some have become commercial success stories. For example, root weevils attacking citrus in Florida (including *Diaprepes abbreviatus* and *Pachnaeus* spp.) have become the largest US target for commercially produced nematodes. Approximately 20,000 ha of citrus were treated with *S. riobrave* to control citrus root weevils in

Nematodes as Biocontrol Agents (eds P.S. Grewal, R.-U. Ehlers and D.I. Shapiro-Ilan)

1999 (M. Dimock, Certis USA, Columbia, MD, 2003, personal communication). In this chapter, we review significant research on EPN control of orchard pests indicating successes and failures, research needs and potential for the future.

11.2. Apples, Pears and Stone Fruits

11.2.1. Lepidopteran pests

11.2.1.1. Codling moth

Codling moth, *Cydia pomonella*, is a key worldwide tortricid pest of apple, pear, walnut and other fruit. The most vulnerable stages in terms of microbial control with EPNs are the full-grown larvae after they exit the fruit, and the cocooned prepupae and pupae. *C. pomonella* overwinter as full-grown cocooned larvae in cryptic habitats (under bark, within prop piles, fruit bins and leaf litter). Research results indicate good *C. pomonella* control potential with *Steinernema carpocapsae* (which was originally isolated from *C. pomonella* (Weiser, 1955)) and a number of other nematode species when adequate moisture is maintained and temperatures are above 10–15°C (Kaya *et al.*, 1984; Sledzevskaya, 1987; Nachtigall and Dickler, 1992; Lacey and Unruh, 1998; Lacey and Chauvin, 1999; Unruh and Lacey, 2001). Dosages in the range of $1–2 \times 10^6$ infective juveniles (IJs) per tree and surrounding area can provide effective control of cocooned larvae under optimum conditions of adequate moisture and temperature. Protocols for the field evaluation of EPNs against cocooned stages of *C. pomonella* are presented by Lacey *et al.* (2000). The major obstacles for successful *C. pomonella* control are low temperatures and desiccation of IJs. Ideally, sprayed trees and surrounding areas should be kept moist for 8 h or more (Lacey and Unruh, 1998; Unruh and Lacey, 2001). Recent research indicates EPNs to be compatible with other biocontrol agents (e.g. ichneumonid parasitoids) for *C. pomonella* control (Lacey *et al.*, 2003).

Fruit bins infested with cocooned *C. pomonella* can be a significant source of invading moths in mid-to late summer when they are placed in orchards for harvest. EPNs offer potential for decontaminating fruit bins when they are submerged in drop tanks (Lacey and Chauvin, 1999) or sprayed with drenchers used for treating or cooling fruit (Cossentine *et al.*, 2002).

11.2.1.2. Other lepidopteran pests

A variety of other lepidopterans are pests of apple, pear and stone fruits to varying degrees, depending on locality. EPNs offer a narrow window of opportunity for control of defoliating Lepidoptera that have soil stages. Noctuids, for example, are most vulnerable as prepupae when they search for a soil site in which they pupate. Laboratory studies demonstrated fair to good activity of several nematode species against leafrollers (torticids that construct retreats in rolled leaves or shoots), e.g. the obliquebanded leafroller, *Choristoneura rosaceana* (Poinar, 1991; Belair *et al.*, 1999). However, only limited field trials have been conducted without evidence of effective control (Belair *et al.*, 1999). A major apple pest in China, *Carposina nipponensis*, has been shown to be highly susceptible to EPN control; field trials resulted in greater than 90% larval mortality (Bedding, 1990). Additionally, substantial efficacy of *Steinernema* spp. against species of tree borers in the genus *Synanthedon* has been demonstrated in apple and stone fruit orchards (Deseö and Miller, 1985; Cossentine *et al.*, 1990; Kahounova and Mracek, 1991). In contrast, field trials to suppress another lepidopteran borer, the American plum borer, *Euzophera semifuneralis*, did not provide any significant control with *S. feltiae* or *Heterorhabditis bacteriophora* (Kain and Agnello, 1999).

11.2.2. Non-lepidopteran pests

11.2.2.1. Fruit flies

Some of the most harmful pests of cherries are fruit flies. Research demonstrates that several species of fruit flies are susceptible to EPNs (Beavers and Calkins, 1984;

Lindegren and Vail, 1986; Lindegren *et al.*, 1990; Gazit *et al.*, 2000), but most investigations have been limited to laboratory research. The western cherry fruit fly, *Rhagoletis indifferens* (a serious pest of sweet cherries in western USA), has been investigated for control using *Steinernema* spp. and *Heterorhabditis* spp. under laboratory and field conditions (Patterson Stark and Lacey, 1999; Yee and Lacey, 2003). Yee and Lacey (2003) evaluated *S. carpocapsae*, *S. feltiae* and *S. intermedium* in soil against *R. indifferens* larvae, pupae and adults in the laboratory. Larvae were the most susceptible stage, with mortality ranging from 62% to 100%. *S. carpocapsae* and *S. feltiae* were equally effective against larvae at 50 and 100 IJs/cm^2. Mortalities of *R. indifferens* larvae 0–6 days following their introduction into soil previously treated with 50 IJs/cm^2 of *S. carpocapsae* or *S. feltiae* were 78.6–77.5%. Pupae were not infected, but adult flies were infected by all three nematode species in the laboratory at a concentration of 100 IJs/cm^2. In field trials *S. carpocapsae* and *S. feltiae* were equally effective against larvae (59–85% mortality) when applied to soil under cherry trees at 50–100 IJs/cm^2. Because abandoned orchards and trees in yards of homeowners represent a threat to commercial cherry orchards by providing significant sources of invading flies, Yee and Lacey (2003) proposed the use of EPNs in these situations for the control of *R. indifferens*.

11.2.2.2. Other non-lepidopteran pests

There are a wide variety of other non-lepidopteran pests of apple, pears and peaches, but EPNs have only been evaluated against a few species. Vincent and Belair (1992) and Belair *et al.* (1998) reported control of the apple sawfly, *Hoplocampa testudinea*, with EPNs. Applications of *S. carpocapsae* every 2–3 days from early May until mid-June by Belair *et al.* (1998) reduced primary damage caused by larvae of *H. testudinea* by 98–100% in two seasons (1992–1993), but treatments were ineffective in the following year. The western flower thrips, *Frankliniella occidentalis*, attack a wide range of crops and can be a pest of several fruit varieties including apple, pear and cherry. Potential for control of thrips has been demonstrated with EPNs (Helyer *et al.*, 1995; Ebssa *et al.*, 2001a,b) and *Thripinema nicklewoodi* (Lim *et al.*, 2001; Arthurs and Heinz, 2003; see Chapter 22, this volume). Similarly, other thrip pests such as *Taeniothrips inconsequens* (a serious pest of pear and plum) may be susceptible to nematodes.

The plum curculio, *Conotrachelus nenuphar*, is a key pest of apple and stone fruits in North America. Belair *et al.* (1998) applied *S. carpocapsae* for control of *C. nenuphar* in apples and observed highly variable results ranging from 75% damage reduction to no significant reduction. In laboratory studies comparing six nematode species, Shapiro-Ilan *et al.* (2002a) reported *S. feltiae* and *S. riobrave* to be most virulent to *C. nenuphar* larvae, whereas *S. carpocapsae* and *S. riobrave* were the most virulent to *C. nenuphar* adults. In field trials in peach orchards, Shapiro-Ilan *et al.* (2004) observed, on average, greater than 90% suppression of *C. nenuphar* larvae with *S. riobrave*.

11.3. Nut Crops

11.3.1. Navel orangeworm

The navel orangeworm, *Amyelois transitella*, is a serious pest of almonds, walnuts and pistachio (Rice, 1978a,b) and the most important pest of almonds in the USA. The larval stage invades nuts during hull split and feeds on the nutmeats. The larvae infest mature nuts on the tree and nut mummies on the tree and ground. Conventional control of *A. transitella* during the growing season is through the application of organophosphate, carbamate and other insecticides. Orchard sanitation is also an important aspect of navel orangeworm control. Nut mummies are removed from the trees by shaking, polling, pruning, etc. and blown into furrows for disking (in pistachios) or flail mowing (in almonds).

rendering the majority of the nuts unsuitable for development of larvae. However, some larvae survive this treatment and pose a significant threat to nuts in the following season. In addition to the need for insecticides to protect nuts from moths that have survived sanitation measures, there are air quality problems (dust) generated by disking, blowing and flail mowing. The use of EPNs offers an alternative means of control that will help reduce the use of pesticides and improve air quality. However, initial investigations on the potential of EPNs for control of the moth were not especially promising. Summer-time field application of the nematode *S. carpocapsae* to open hulled almonds resulted in over 65% mortality in baited *A. transitella* (Lindegren *et al.*, 1987), whereas dormant season (winter) application of EPNs to trees resulted in substantially lower control (Agudelo-Silva *et al.*, 1995). Siegel *et al.* (2004) studied the efficacy of *S. carpocapsae* and *S. feltiae* applied to almond and pistachio nut mummies on the ground for control of *A. transitella* larvae. Larvae were almost completely controlled with *S. carpocapsae* at 10^5 IJs/m^2 and to a lesser extent by *S. feltiae* at the same dosage. The low rate of applications used to achieve these high levels of control indicates that ground application of EPNs as a sanitation tool for *A. transitella* is a highly promising tactic and should be pursued further. EPNs persist well in this environment, offering the potential of recycling within the *A. transitella* population (Agudelo-Silva *et al.*, 1987; Siegel *et al.*, 2004).

11.3.2. Pecan weevil

The pecan weevil, *Curculio caryae*, is a key pest of pecans throughout southeastern USA as well as portions of Kansas, Oklahoma and Texas (Shapiro-Ilan, 2003). Adults emerge from soil in late July–August and feed on and oviposit in developing nuts. Larvae develop in the nuts, drop to the soil, burrowing to a depth of 8–25 cm, and form a soil-cell where they spend 1 year (and sometimes 2) before pupating and moulting to adulthood; adults spend approximately 9 additional months in the soil before emerging (Harris, 1985). Control recommendations for the pecan weevil currently consist solely of above-ground applications of chemical insecticides (mainly carbaryl) to suppress adults (Hudson *et al.*, 2003).

11.3.2.1. Potential to control larvae with entomopathogenic nematodes (EPNs)

EPNs have been reported to occur naturally in *C. caryae* larvae (Harp and Van Cleave, 1976; Nyczepir *et al.*, 1992). Yet field applications to suppress larvae (with *H. bacteriophora*, *S. carpocapsae* or *S. feltiae*) resulted in less than 35% control unless exceedingly high rates were used (Tedders *et al.*, 1973; Nyczepir *et al.*, 1992; Smith *et al.*, 1993). In order to determine if other nematode species might have greater virulence to *C. caryae* larvae than those tested previously, Shapiro-Ilan (2001a) conducted a laboratory study including nine nematode species and 13 strains. The level of *C. caryae* mortality observed was low to moderate (not more than 60%) for all nematodes tested, and no significant differences in virulence were detected among the species (Table 11.1). Additionally, Shapiro-Ilan, (2001a) demonstrated that nematode virulence to *C. caryae* larvae is substantially less compared with virulence to the Diaprepes root weevil, *D. abbreviatus*, a weevil that is currently controlled commercially by EPNs in some citrus orchards (see Section 11.4.). Susceptibility of *C. caryae* larvae to nematodes was shown to decrease further with larval age (Shapiro-Ilan, 2001a). Thus, Shapiro-Ilan (2001a) concluded that suppression of *C. caryae* larvae with EPNs is unlikely to be cost effective unless virulence can be substantially improved.

11.3.2.2. Potential to control adults

Adult pecan weevils may be more amenable to control with EPNs than larval-stage weevils (Shapiro-Ilan, 2001b, 2003). Laboratory studies conducted under parallel conditions

Table 11.1. Pecan weevil, *Curculio caryae*, control following exposure to entomopathogenic nematodes (EPNs) under laboratory conditions.[a]

Nematode (strain)	*C. caryae* stage	*C. caryae* control[b]
Heterorhabditis bacteriophora (Baine)	Larval	21.3a
H. bacteriophora (HP88)	Larval	41.0a
H. bacteriophora (NJ1)	Larval	42.7a
H. indica (Hom1)	Larval	40.9a
H. indica (original)	Larval	47.5a
H. marelatus (IN)	Larval	42.7a
H. marelatus (Point Reyes)	Larval	45.9a
H. megidis (UK211)	Larval	36.1a
H. zealandica (NZH3)	Larval	23.0a
Steinernema carpocapsae (All)	Larval	30.4a
S. feltiae (SN)	Larval	23.0a
S. glaseri (NJ43)	Larval	32.8a
S. riobrave (355)	Larval	37.7a
H. bacteriophora (Hb)	Adult	67.0b
H. bacteriophora (Oswego)	Adult	48.0bc
S. carpocapsae (All)	Adult	99.0a
S. feltiae (SN)	Adult	40.0c
S. riobrave (355)	Adult	67.0b

[a] Mortality was determined after 13-day (larvae) or 4-day (adults) exposure to 500 infective juveniles (IJs).

[b] Following correction for control mortality using Abbott's (1925) formula.

Note: Different letters following each number indicate statistical significance within each *C. caryae* stage. Data on larval control is presented with permission of the Entomological Society of America, *Journal of Economic Entomology* 94, 7–13; data on adult control is presented with the permission of the *Journal of Entomological Science* 36, 325–328.

used for the larvae (Shapiro-Ilan, 2001a) indicated high virulence of several nematodes to pecan weevil adults (Table 11.1) (Shapiro-Ilan, 2001b, 2003). *S. carpocapsae* was particularly virulent, killing close to 100% of the weevils; *S. riobrave* and *H. bacteriophora* also showed some potential (Shapiro-Ilan, 2001b, 2003). One economical approach for adult control may be to apply EPNs in a narrow (perhaps 1–2 m) band around each pecan tree to infect the weevils that crawl to the tree. If the banding method does not infect a satisfactory proportion of weevils, the application area would have to be expanded to cover the entire area of weevil emergence (i.e. under the tree's canopy).

Recent field trials (using the banding method) indicate *S. carpocapsae* (All) can provide 60–80% control of emerging *C. caryae* adults (Shapiro-Ilan, 2003; unpublished data), but this level of control is short-lived (not exceeding 1 week). The efficacy of this nematode might be improved by selecting a superior strain. Towards this end, Shapiro-Ilan *et al.* (2003) compared eight *S. carpocapsae* strains for various beneficial traits (virulence to adult weevils, environmental tolerance and reproductive capacity). Based on a novel beneficial trait ranking system, Breton, DD136, Italian, and Kapow strains were graded inferior to other strains, and Agriotos, All and Sal strains superior. Other important traits will need to be assessed (e.g. longevity) before a choice is made as to which strain(s) might be most suitable for *C. caryae* control. If none of the naturally occurring strains provide superior *C. caryae* suppression, then traits might be improved further through artificial selection (Gaugler *et al.*, 1989) or targeted hybridization (Shapiro *et al.*, 1997). In addition to research towards strain improvement, other parameters that must be investigated further to optimize control include irrigation requirements, and rate, method and area of application.

11.4. Citrus

11.4.1. Root weevils

Citrus is host to a complex of curculionid species that feed on the leaves and roots of trees. Most weevil species are of little economic importance; however, *D. abbreviatus* is a major pest responsible for annual losses of US$75–100 million by citrus growers in Florida and the Caribbean Basin (McCoy, 1999). The weevil infests more than 20,000 ha of citrus throughout Florida, and its range is expanding (Hall, 1995). The blue-green weevils, *Pachnaeus* spp., are also pests of citrus in Florida, although resulting damage is less severe than from *D. abbreviatus*. Like *D. abbreviatus*, *Pachnaeus* spp. are polyphagous. On citrus, they feed on young leaves, and eggs are oviposited on leaf surfaces (Fig. 11.1). The neonate larvae fall to the soil where they develop to adults over the next several months. Egg laying occurs from early summer until winter, and teneral adults emerge from the soil throughout the year (Nigg *et al.*, 2003). While in the soil, the larvae feed on the fibrous and major roots of citrus trees. Feeding by late instar larvae of *D. abbreviatus* causes severe damage to roots in the crown of the tree. Wounding of the root cortex also creates infection sites for *Phytophthora* spp., resulting in a pest–disease complex that severely debilitates and even kills trees (Graham *et al.*, 2003). There are no chemical pesticides registered in Florida for management of the soil-borne stages of weevil. Various commercially formulated EPNs have been used for this purpose since 1990.

11.4.2. Nematode efficacy

The earliest attempts to manage *D. abbreviatus* with EPNs involved laboratory studies and field trials to evaluate *S. glaseri*, *S. carpocapsae* and *H. bacteriophora*

Diaprepes abbreviatus* life cycle

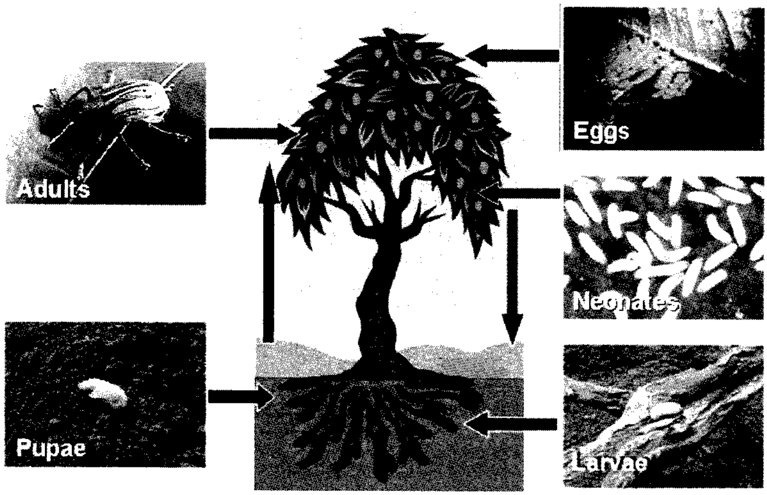

Fig. 11.1. *Diaprepes abbreviatus* life cycle. Adult weevils feed on young foliage and cement egg masses between leaves for protection. When neonate larvae hatch they fall to the soil where they feed on progressively larger roots for several months before pupating. Teneral adults emerge from the soil to reinitiate the cycle. (Note the extensive feeding channels on structural roots that promote infection by *Phytophthora* spp. Figure courtesy of Robin Stuart, University of Florida.)

(Schroeder, 1987, 1990, 1992; Downing *et al.*, 1991; Bullock and Miller, 1994). When the latter two species were used in field trials at rates ranging from 100 to 600 IJs/cm^2, the emergence of adult weevils was suppressed by as much as 60–80% for up to 1 year following treatment. Those trials resulted in widespread use of commercially formulated *S. carpocapsae* and *H. bacteriophora* by citrus growers in Florida (Fig. 11.2). Grower acceptance of EPNs resulted from the lack of effective pesticides to manage an economically important pest, and the reasonably low cost of nematode products. Despite their widespread use, the efficacy of products containing *S. carpocapsae* and *H. bacteriophora* was less apparent in subsequent field trials (Adair, 1994; Duncan and McCoy, 1996; Duncan *et al.*, 1996). In contrast, commercially formulated *S. riobrave* at rates of 100 IJs/cm^2 was found to reduce numbers of adults and weevil larvae in the rhizosphere of young trees by 80–95% within 15–30 days post-treatment (Duncan and McCoy, 1996; Duncan *et al.*, 1996; Bullock *et al.*, 1999). Laboratory trials using these and six additional EPN species revealed that *S. riobrave* and a Florida isolate of *H. indica* were significantly more effective against *D. abbreviatus* than other species evaluated, and that *H. indica* reproduces at exceptionally high levels in the insect (Schroeder, 1994; Shapiro *et al.*, 1999; Shapiro and McCoy, 2000a,b). *S. riobrave* and *H. indica* are currently the only two EPN species that are marketed in the Florida citrus industry. In 1999, approximately 20% of the hectarage infested with *D. abbreviatus* was treated with EPNs (Shapiro-Ilan *et al.*, 2002b). Populations of *Pachnaeus* spp. and *Phytophthora nicotianae* are also reduced by application of EPNs (Bullock *et al.*, 1999; Duncan *et al.*, 2002).

11.4.2.1. Factors affecting nematode efficacy

Major issues that have emerged during evaluation of commercial nematodes include product quality, application dosage, lack of persistence and regional variation in efficacy. Quality control of some nematode products has occurred periodically. Quality issues have proven correctible, but they are a serious concern because they result in reduced acceptance by growers and advisors for use of nematodes as a viable management tactic.

Generally, high levels of *D. abbreviatus* suppression have been achieved with appli-

Fig. 11.2. Methods for application of entomopathogenic nematodes (EPNs) in citrus orchards. Nematodes can be suspended in water in clean chemical-mixing tanks (A) and injected under pressure into the main irrigation line (B) for delivery via microjet-irrigation sprinklers (C). Nematodes can also be delivered via clean herbicide application equipment (D) and incorporated with irrigation. (Photographs by Gretchen Baut.)

cation rates of at least 100 IJs/cm^2. Rates recommended for *D. abbreviatus* control by commercial suppliers have tended to be considerably lower (the actual rate per unit area can depend on the size of the undercanopy being treated). Use of lower application rates can result in reduced (or absence of) efficacy and profitability (McCoy *et al.*, 2000, 2002), but the extent to which growers can increase rates in mature orchard application is constrained by cost. Suppression of larvae in soil by application of nematodes is ephemeral, in the order of 1 or 2 weeks (McCoy *et al.*, 2000, 2002). Neonate larvae soon replace many of those that were killed by nematodes. Similarly, suppression of the numbers of adult insects with non-persistent insecticides is quickly negated by recruitment of teneral adults that emerge from the soil throughout the year. Thus, there is a critical need for management tactics with greater residual activity, and the role of EPNs in future integrated pest management (IPM) programmes is unclear. The development of insect-resistant rootstocks or physical soil barriers could reduce or obviate the need for inundatively applied nematodes, as has occurred in other systems (Shapiro-Ilan *et al.*, 2002b).

Regional variation in efficacy of EPNs has become apparent (Table 11.2). Measurable efficacy has been demonstrable in most field trials conducted on Florida's central ridge (Duncan and McCoy, 1996; Duncan *et al.*, 1996, 1999, 2002, 2003), whereas efficacy has been variable, and generally poor, in trials conducted in the flatwoods regions (Adair, 1994; Stansly *et al.*, 1997; Bullock *et al.*, 1999; McCoy *et al.*, 2000, 2002). Soil texture has been implicated as a potential factor responsible for variation in efficacy (Duncan *et al.*, 2001; McCoy *et al.*, 2002). The central ridge is characterized by deep, well-drained sandy soil, whereas soils in the coastal and central flatwood areas vary in texture and factors such as salinity and drainage. Additional work is needed to characterize the edaphic factors that modulate the effectiveness of EPNs.

11.4.3. Towards regional IPM of *Diaprepes abbreviatus*

A broad continuum of damage is exhibited by orchards infested with *D. abbreviatus*. Population densities of the weevil are typically lower on the central ridge than in some regions of the flatwoods (Futch, 2002) and tree damage varies accordingly. Natural enemies may cause some of the variation in weevil population density. Endemic EPNs attack *D. abbreviatus* throughout Florida (Beavers *et al.*, 1983; Nguyen and Duncan, 2002) and were found to infect weevil larvae in soil at an average rate of 55% per week in an orchard on the central ridge compared with only 8% in an orchard on fine-textured soil in the flatwoods (Duncan *et al.*, 2003). Fine-textured, poorly drained soils are also conducive to root infection by *Phytophthora* spp. (Graham *et al.*, 2003). Flooded soil predisposes trees to greater stress from *D. abbreviatus* herbivory (Li *et al.*, 2003). Thus, a combination of edaphic factors and natural enemies may modulate the damage caused by this pest–disease complex by stressing trees and regulating the population densities of the causal agents. Additional study of regional factors that regulate damage by *D. abbreviatus* is warranted for several reasons. First, the central ridge may represent an important niche in which EPNs can be used profitably to reduce these pests below an economic threshold. Trees in some flatwood orchards may respond less favourably to nematode treatments, either because edaphic conditions are less conducive to these nematodes, tree stress is excessive, or because the pest pressure is too high to be reduced by nematodes to a non-damaging level. Second, in regions conducive to nematode activity, infection of weevil larvae by endemic nematodes can occur at a higher rate over time than that exhibited by exotic nematodes applied for insect control (Duncan *et al.*, 2003). This suggests a need to conserve the level of endemic nematodes, either by selection of application times that reduce competition with exotic nematodes or by augmentation with endemic species adapted to local conditions. Finally, a better under-

Table 11.2. Field efficacy of *Steinernema* and *Heterorhabditis* nematodes against *Diaprepes* root weevil.

Nematode	Application rate (cm^2)	% mortality[a]	References
Heterorhabditis bacteriophora	127	78	Downing *et al.*, 1991
H. bacteriophora	255	63	Downing *et al.*, 1991
H. bacteriophora	637	63	Downing *et al.*, 1991
H. bacteriophora	100	62	Schroeder, 1992
H. bacteriophora	250	0	Duncan and McCoy, 1996
H. bacteriophora	175	54	Duncan *et al.*, 1996
H. bacteriophora	255	57	Duncan *et al.*, 1996
H. bacteriophora	11	8	McCoy *et al.*, 2000
H. bacteriophora	22	8	McCoy *et al.*, 2000
H. indica	11	14	McCoy *et al.*, 2000
H. indica	22	19–21	McCoy *et al.*, 2000
H. indica	54	28	McCoy *et al.*, 2000
H. indica	11	0	McCoy *et al.*, 2002
H. indica	54	0	McCoy *et al.*, 2002
H. indica	108	27	McCoy *et al.*, 2002
Steinernema carpocapsae	250	65	Schroeder, 1987
S. carpocapsae	25	42	Schroeder, 1990
S. carpocapsae	100	50	Schroeder, 1992
S. carpocapsae	637	48	Downing *et al.*, 1991
S. carpocapsae	1666	57–82	Bullock and Miller, 1994
S. carpocapsae	153	0	Duncan *et al.*, 1996
S. carpocapsae	306	0	Duncan *et al.*, 1996
S. glaseri	250	35	Schroeder, 1987
S. riobrave	250	77–90	Duncan and McCoy, 1996
S. riobrave	120	93	Duncan *et al.*, 1996
S. riobrave	110	0–98	Bullock *et al.*, 1999
S. riobrave	ND	48–100	Bullock *et al.*, 1999
S. riobrave	11	0	McCoy *et al.*, 2002
S. riobrave	54	0–8	McCoy *et al.*, 2002
S. riobrave	108	0–36	McCoy *et al.*, 2002
S. riobrave	22	5–22	McCoy *et al.*, 2000
S. riobrave	54	30–49	McCoy *et al.*, 2000
S. riobrave	108	32–34	McCoy *et al.*, 2000
S. riobrave	216	63	McCoy *et al.*, 2000
S. riobrave	20	0–66	Duncan *et al.*, 2003

[a] Percentage mortality in treated plots, corrected for mortality in control plots. Statistical significance of treatment responses is not indicated in the table.

standing of regional factors that regulate numbers of *D. abbreviatus* may result in new insights for managing this pest in conditions that are poorly suited to the use of EPNs.

11.5. Banana

Bananas, which are grown in the tropical and subtropical areas, are a widely available fruit throughout the world. The banana stem borer, *Odoiporus longicollis*, and the banana weevil borer, *Cosmopolites sordidus*, are the most important pests. Nematodes have been used to control these pests in Australia and China, with encouraging results. These two species of insect usually occur throughout the year. The larvae and some adults feed on the base stem of the plant and bore into the stem, weakening or killing the plant.

In southern China, *O. longicollis* has six generations per year with two population peaks in March–June and November–December. Usually, the corms of the trees are cut at the base in winter after harvest. Approximately 90% of the overwintering populations in the residual stems of the banana plants are larvae that attack the banana stems the following year. EPNs are capable of migrating through living stem tissue to kill the borers; field results indicated that 76–90% of the overwintering larvae, 68–92% of the pupae and 25–80% of *O. longicollis* adults were controlled by spraying 3–6 × 10^6 IJs of *S. carpocapsae* (A24) into each residual stem base (Xu *et al.*, 1991).

C. sordidus is a major pest of bananas and plantains. Larvae burrow into corms producing severe damage, which can be exacerbated by subsequent fungal or bacterial attack. Laumond *et al.* (1979) demonstrated pathogenicity of *S. carpocapsae* to adult *C. sordidus* in laboratory trials. Figueroa (1990) demonstrated pathogenicity of several nematode species (*S. carpocapsae*, *S. feltiae* and *S. glaseri*) to *C. sordidus* larvae, and observed 100% mortality in greenhouse tests using 4000 IJs per plant. Field applications of *S. carpocapsae* in a water-thickening gel (used to keep the nematodes near the target site) to cuts or holes made in the residual banana rhizomes has provided control of larvae and adults that were attracted to cut surfaces (Treverrow *et al.*, 1991). In similar research (R. Han, 2002, unpublished data), slashing of corms at the base followed by nematode application in a polyacrylamide gel spread over the cut surface provided control of larvae as well as adults attracted to the cut corm. Kermarrec and Mauléon (1989) reported that the effects of *S. carpocapsae* on *C. sordidus* can be enhanced through synergistic interactions with chemical insecticides (e.g. chlordecone).

11.6. Litchi

Litchi is an important and high-value crop in several Asian countries, such as China, Thailand and Vietnam. In Guangdong, China, which is climatically very well suited to production of this fruit, there are over 150,000 ha of litchi orchards, comprising an estimated 30 million litchi trees. Most litchi trees are productive for 20–100 years. The value of this crop in Guangdong is over US$190 million per year, for domestic and export markets combined. The key litchi pests are the litchi stem borer, *Arbela dea*, and the litchi longhorn beetle, *Aristobia testudo*.

11.6.1. Litchi stem borer

A. dea has one generation per year, the larval stage is the damaging stage and lasts up to 9 months, beginning in June. As first instars, *A. dea* damage the lower bark of the litchi tree and then bore into the trunk as they mature. Resulting damage can weaken the trees, or cause death, depending on the litchi strain, age and location.

A. dea is susceptible to *S. carpocapsae* (A24). The nematodes are applied by conventional sprayers around the borer holes. The *A. dea* larvae are usually active just outside the borer holes at night, providing an ideal place for contact between the nematodes and the insects. Thus, the nematodes do not need to be applied directly into the borer holes (e.g. by injection), which would increase labour. Over 86% *A. dea* mortality was obtained by spraying 1000 IJs around each borer hole (Xu and Yang, 1992).

11.6.2. Litchi longhorn beetle

The most important litchi pest is *A. testudo*, which causes great economic losses to the crop. Similar to *A. dea*, *A. testudo* has one generation per year. The adults of this beetle lay eggs between the crotches of litchi trees. The hatched larvae, whose distribution is aggregative, bore into the stem and develop in the holes for up to 9 months (Han *et al.*, 1994). Without control the infested branches wither and die, resulting in no fruit yield.

Most tactics to control *A. testudo* are ineffective due to the inaccessibility of the larvae in tunnels. Mobile nematodes, on the other hand, actively search for the larvae of the beetle in the deepest recesses, and have been shown to produce over 73% mortality following injection of 3000 IJs *S. carpocapsae* (A24) into the freshly bored holes of the beetle (Xu *et al.*, 1995; Han *et al.*, 1996).

Successful pest control was achieved in 1700 ha of litchi orchards in Guangdong. As a result, farmers' interest in utilization of EPNs as a safe and effective control of these pests has been generated. Producers of EPNs have been less interested, however, due to competition from chemical insecticides and the relatively limited hectarage occupied by litchi pests. None the less, successful field demonstrations indicate the potential of EPNs to control these pests. Further research will focus on strain selection and formulation development to enhance migration ability and desiccation tolerance.

11.7. Summary and Conclusions

EPNs are being applied commercially for control of some important insect pests of orchards (e.g. *D. abbreviatus* and *Pachnaeus* spp. in citrus), and there are a number of cases where commercial application may be within reach: *C. pomonella* in apples, *R. indifferens* in cherries, *A. transitella* in almonds and pistachio, *C. caryae* in pecans, *C. nenuphar* in apple and stone fruits, *O. longicollis* and *C. sordidus* in banana and *A. dea* and *A. testudo* in litchi. To improve and expand the use of EPNs as inundative biocontrol agents for orchard pests, advances in research are required, particularly in reducing costs of production and application, and methodology to improve persistence of nematodes in soil or in the canopy. Additionally, inoculative or conservation approaches to biocontrol with nematodes must be explored. Various conditions associated with orchards as agroecosystems may facilitate these approaches, e.g. plant species and structural diversity, soil conditions and stability (Kaya, 1990; Barbosa, 1998; Lewis *et al.*, 1998). Various characteristics and management practices such as soil types, fertilization, irrigation, crop covers, etc. should be investigated within each specific orchard system to determine their effects on EPN ecology and potential to improve long-term efficacy.

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