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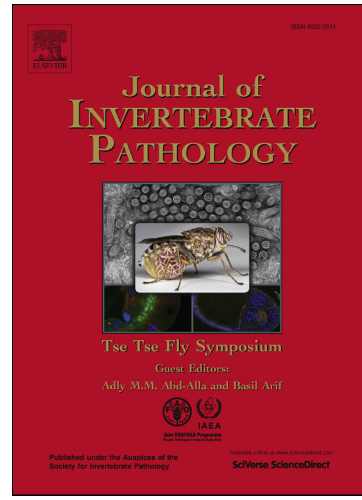

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Insect pathogens as biological control agents: back to the future

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Abstract

The development and use of entomopathogens as classical, conservation and augmentative biological control agents have included a number of successes and some setbacks in the past 15 years. In this forum paper we present current information on development, use and future directions of insect-specific viruses, bacteria, fungi and nematodes as components of integrated pest management strategies for control of arthropod pests of crops, forests, urban habitats, and insects of medical and veterinary importance.

Insect pathogenic viruses are a fruitful source of MCAs, particularly for the control of lepidopteran pests. Most research is focused on the baculoviruses, important pathogens of some globally important pests for which control has become difficult due to either pesticide resistance or pressure to reduce pesticide residues. Baculoviruses are accepted as safe, readily mass produced, highly pathogenic and easily formulated and applied control agents. New baculovirus products are appearing in many countries and gaining an increased market share. However, the absence of a practical *in vitro* mass production system, generally higher production costs, limited post application persistence, slow rate of kill and high host specificity currently contribute to restricted use in pest control. Overcoming these limitations are key research areas for which progress could open up use of insect viruses to much larger markets.

A small number of entomopathogenic bacteria have been commercially developed for control of insect pests. These include several *Bacillus thuringiensis* sub-species, *Lysinibacillus* (*Bacillus*) *sphaericus, Paenibacillus* spp. and *Serratia entomophila*. *B. thuringiensis* sub-species *kurstaki* is the most widely used for control of pest insects of crops and forests, and *B. thuringiensis* sub-species *israelensis* and *L. sphaericus* are the primary pathogens used for medically important pests including dipteran vectors,. These pathogens combine the advantages of chemical

pesticides and microbial control agents (MCAs): they are fast acting, easy to produce at a relatively low cost, easy to formulate, have a long shelf life and allow delivery using conventional application equipment and systemics (i.e. in transgenic plants). Unlike broad spectrum chemical pesticides, *B. thuringiensis* toxins are selective and negative environmental impact is very limited. Of the several commercially produced MCAs, *B. thuringiensis* (*Bt*) has more than 50% of market share. Extensive research, particularly on the molecular mode of action of *Bt* toxins, has been conducted over the past two decades. The *Bt* genes used in insect-resistant transgenic crops belong to the Cry and vegetative insecticidal protein families of toxins. *Bt* has been highly efficacious in pest management of corn and cotton, drastically reducing the amount of broad spectrum chemical insecticides used while being safe for consumers and non-target organisms. Despite successes, the adoption of *Bt* crops has not been without controversy. Although there is a lack of scientific evidence regarding their detrimental effects, this controversy has created the widespread perception in some quarters that *Bt* crops are dangerous for the environment. In addition to discovery of more efficacious isolates and toxins, an increase in the use of *Bt* products and transgenes will rely on innovations in formulation, better delivery systems and ultimately, wider public acceptance of transgenic plants expressing insect-specific *Bt* toxins.

Fungi are ubiquitous natural entomopathogens that often cause epizootics in host insects and possess many desirable traits that favor their development as MCAs. Presently, commercialized microbial pesticides based on entomopathogenic fungi largely occupy niche markets. A variety of molecular tools and technologies have recently allowed reclassification of numerous species based on phylogeny, as well as matching anamorphs (asexual forms) and teleomorphs (sexual forms) of several entomopathogenic taxa in the Phylum Ascomycota. Although these fungi have been traditionally regarded exclusively as pathogens of arthropods, recent studies have demonstrated that they occupy a great diversity of ecological niches. Entomopathogenic fungi are now known to be plant endophytes, plant disease antagonists, rhizosphere colonizers, and plant growth promoters. These newly understood attributes provide possibilities to use fungi in multiple roles. In addition to arthropod pest control, some fungal species could simultaneously suppress plant pathogens and plant parasitic nematodes as well as promote plant growth. A greater understanding of fungal ecology is needed to define their roles in nature and evaluate their limitations in biological control. More efficient mass production, formulation and delivery systems must be devised to supply an ever increasing market. More testing under field conditions is required to identify effects of biotic and abiotic factors on efficacy and persistence. Lastly, greater attention must be paid to their use within integrated pest management programs; in particular, strategies that incorporate fungi in combination with arthropod predators and parasitoids need to be defined to ensure compatibility and maximize efficacy.

Entomopathogenic nematodes (EPNs) in the genera *Steinernema* and *Heterorhabditis* are potent MCAs. Substantial progress in research and application of EPNs has been made in the past decade. The number of target pests shown to be susceptible to EPNs has continued to increase. Advancements in this regard primarily have been made in soil habitats where EPNs are shielded from environmental extremes, but progress has also been made in use of nematodes in above-ground habitats owing to the development of improved protective formulations. Progress has also resulted from advancements in nematode production technology using both *in vivo* and *in vitro* systems; novel application methods such as distribution of infected host cadavers; and nematode strain improvement via enhancement and stabilization of beneficial traits. Innovative research has also yielded insights into the fundamentals of EPN biology including major advances in genomics, nematode-bacterial symbiont interactions, ecological relationships, and foraging behavior. Additional research is needed to leverage these basic findings toward direct improvements in microbial control.

1. **Introduction**

Since Lacey et al. (2001) addressed the possible future of microbial control of insects, the development of microbial pesticides and implementation of microbial control has included a number of successes and suffered some setbacks. Entomopathogens are utilized in all three categories of biological control, classical, conservation and augmentative, as defined by Hoy (2008a, 2008b) and McCrevy (2008). Some pathogens that are not commercially produced are currently used as classical biological control agents (Huger, 2005; Hajek, 2007; Hajek et al., 2007, 2008, 2009; Hajek and Delalibera, 2010; Bedding, 2008) or conserved as naturally occurring pathogens in agroecosystems (Hummel et al., 2002; Nielsen et al., 2007; Steinkraus, 2007b; Pell et al., 2010). Augmentative biological control, using inundatively applied microbial control agents (MCAs), is the most common strategy for employing entomopathogens for control of pest arthropods. Over 50 entomopathogenic viruses, bacteria, fungi, and nematodes are now commercially produced and used augmentatively as microbial pesticides (Figure 1) (Jackson, 2003; Goettel et al., 2005; Grewal et al., 2005; Ekesi and Maniania, 2007; Kaya and Lacey, 2007; Alves and Lopes, 2008; Copping, 2009; Ravensberg, 2011; Glare et al., 2012; Shapiro-Ilan et al, 2012b; Morales-Ramos et al., 2014). On a global scale, microbial pesticides only account for approximately 1-2% of all pesticides sold (Thakore, 2006; Marrone, 2007; Bailey et al., 2010); however, they have shown long term growth over the past decade in contrast to chemical pesticides, which have consistently declined in the global market (Thakore, 2006; Bailey et al

2010). Some sources have recently estimated that the growth in microbial pesticides could reach 3% of the pesticide market in 2014 (Glare et al., 2012). A potent driving force for this expansion is the impact of European legislation to restrict residue levels of most synthetic chemical pesticides, and also a forthcoming directive (EC 91/414) to ban many other pesticides including those deemed to be human endocrine disrupters (Ansell, 2008; Bielza et al., 2008; Marx-Stoelting, et al. 2011). These regulations are increasingly requiring farmers growing horticultural produce for sale in the European Union (EU) to drastically reduce use of conventional broad spectrum chemical pesticides. Expansion in biopesticide markets in Europe also reflects the effort of biocontrol scientists to rationalize and simplify the EU microbial pesticide registration procedures as part of the Regulation of Biological Control Agents (REBECA) project, and create a more favorable regulatory system that supports efforts of companies to commercialize MCAs (Ehlers, 2007). The global adoption of harmonized and simpler registration protocols would be a valuable step to promote wider MCA commercial availability (Ehlers 2007; Cherry and Gwynn, 2007; Bailey et al., 2010; Kabaluk et al., 2010; Meeussen, 2012; Thornström, 2012). The impact of the growing organic sector in horticulture has also played a role in increasing market opportunities for biopesticides (Rohner-Thielen, 2005). Of the several commercially produced MCAs, *Bacillus thuringiensis* has the majority of market share (Glare et al., 2012) (Figure 1).

Entomopathogens are ready made for use in integrated pest management programs and sustainable agriculture (Berger et al., 2007; Pell, 2007; Alves et al., 2008; Lacey and Shapiro-Ilan, 2008; Birch et al., 2011; Glare et al., 2012). They are safe for applicators, the food supply and environment (Lacey and Siegel, 2000; OECD, 2002; Akhurst and Smith, 2002; Hokkanen and Hajek, 2003; Lacey and Merritt, 2003; Hajek and Goettel, 2007; O'Callaghan and Brownbridge, 2009; Mudgal et al., 2013), and their specificity minimizes impacts on beneficial and other non-target organisms. This in turn promotes biodiversity and natural control of pest arthropods by parasites and predators. In the following sections we present information on the current status of entomopathogens as MCAs and prospects for their use in the near and distant future. Some of the key questions that we propose to address are: What are the major advances in microbial control that have been made since 2001? How do we expect biological control to change in the next decade or and in the more distant future? What are the major research or implementation barriers that must be overcome to significantly expand the use of MCAs? What are the societal factors that may hinder or promote their use in the near and distant future?

2. Entomopathogenic viruses

2.1 Major advances since 2001

The role of entomopathogenic viruses in global crop protection has grown in the last decade, although steadily and evolutionarily rather than through any major technical advance. Most new virus products are based on species that have been known and studied for at least two decades and represent commercialization based on extant knowledge rather than recent research efforts. Insect viruses appear to be moving out of narrow "niche" biological control products into the mainstream of commercial farming, reflected in the increased availability of commercial viral pesticides over the last few years. Among the different groups of entomopathogenic viruses (Miller and Ball, 1998; Eberle et al., 2012), most product development and research continues to be focused on the Baculoviridae (BV) (Miller, 1997; Moscardi et al., 2011). Of the four genera of baculoviruses, Alpha-, Beta-, Gamma-, and Deltabaculoviruses (Jehle et al., 2006; Eberle et al., 2012; Herniou et al., 2012), only the lepidopteran-specific nucleopolyhedroviruses (NPV;

Alphabaculovirus spp.) and granuloviruses (GV; Betabaculovirus spp.) have been commercially developed to any significant extent (Table 1).

Research on developing non-BV viruses for crop protection has continued but only to a limited extent. Studies include fieldwork on the use of tetraviruses for control of heliothines in Australia (Christian et al., 2005) and *Cypovirus* spp. (Reoviridae) (Belloncik and Mori, 1998) for control of oil palm pests in South America (Zeddam et al., 2003a), though none appear to be close to commercialization. The use of *Oryctes* virus (Nudiviridae) for control of rhinoceros beetle on oil palm in Asia is an ongoing program (Ramle et al., 2005) that has evolved to include the use of a pheromone to collect adults that are then infected and used to disseminate the virus (Jackson et al., 2005). This is an interesting application of the "lure and infect" approach, although as yet there are no definitive published data on the success of this research and efficacy in the field.

The dearth of research efforts on these non-BV groups is a significant barrier to further development as crop protection agents, which is surprising in some ways given the importance of some of the potential target pests. Without necessary progress in the fundamental knowledge of viral taxonomy, pathology, ecology and the development of commercially viable mass production systems, non-BV viruses are unlikely to be attractive targets for commercialization by industry in the next decade.

The focus on BV for commercialization can be ascribed to several favorable factors. There is more basic knowledge about BV biology, pathology and ecology than for any other group of invertebrate viruses, and the wealth of data greatly facilitates product development and registration. In addition, there are many scientists with the necessary knowledge to support commercialization initiatives, and established centers of BV research are more geographically widespread, enabling collaborations between academics and local microbial pesticide companies. High levels of *in vivo* replication of most BV that are of commercial interest is also a key factor in making commercial production potentially economically feasible.

The infective stage of BVs is characterized by circular double stranded DNA within rod shaped nucleocapsids that are encased within occlusion bodies (OB) formed of crystalline protein. The details of BV life history, biology and ecology are covered in detail elsewhere and are not discussed here (see Miller, 1997; Fuxa, 2004; Cory and Myers, 2003; Cory and Evans, 2007; Moscardi et al., 2011; Harrison and Hoover, 2012). The robust nature of the OB is a factor facilitating commercial baculovirus product development as it is readily amenable to formulation, application and long-term storage than non-occluded insect viruses. OBs can be visualized using phase contrast light microscopy, facilitating quantification of BV without the need for electron microscopy, which requires expensive equipment that often is not readily available to microbial pesticide companies. In the last decade, there has been a significant expansion in range of commercial BV products (Kabaluk et al., 2010; Gwynn 2014), notably in the range of BV insecticides available in Europe and North America. Elsewhere the picture is mixed with significant expansion in the production and use of BV microbial pesticides in parts of Asia, Australasia and South America, but as yet little expansion of use in Africa (Cherry and Gwynn, 2007; Kabuluk et al. 2010; Moscardi et al., 2011).

The focus on BV is in large part due to the importance of these pathogens in controlling some globally important lepidopteran pest species such as *Helicoverpa* spp. (Rowley et al. 2011) and *Spodoptera* spp. (Table 1). These pest species have a marked propensity to rapidly develop resistance to conventional chemical insecticides, making their control challenging. These species also are pests on a wide range of crops, providing potential market niches for BV in field crops and in protected crops grown in polytunnels and glasshouses (Grzywacz et al., 2005; Arrizubieta et al., 2014). In China, NPV supply has expanded with nine BV products now commercially available. There are at least 12 Chinese manufacturers of *Helicoverpa armigera* NPV (HearNPV) and several of *Spodoptera litura* NPV (SpltNPV), *Autographa californica* NPV (AucaMNPV), *Plutella xylostella* GV (PlxyGV) and *Spodoptera exigua* NPV (SeMNPV) as well as a number of other BV products (Sun and Peng, 2007;Yang et al., 2012). It is difficult, however, to determine the total use of BV in China. One source estimated that in 2007 around 250 tonnes of formulated material was produced, 80% of which was HearNPV, used on up to 100,000 ha (Sun and Peng, 2007). A more recently published estimate stated that up to 2,000 tonnes of formulated BV products may be produced annually, from which it may be inferred that areas treated have expanded significantly from the earlier estimate, and may have reached up to 1 million ha (Yang et al., 2012). In India, many new suppliers of HearNPV and SpltNPV have appeared in recent years following the adoption of simplified microbial pesticide registration and in response to the growing problem of synthetic insecticide resistance (Department of Biotechnology India, 2007; Rabindra and Grzywacz, 2010). The total production of BV in India was estimated to be in excess of 50 tonnes in 2004 (Singhal, 2004) with both public and private sector organizations active in manufacturing. Quality control issues remain a concern in India and parts of Southeast Asia (Jenkins and Grzywacz 2000; Kambrekar et al., 2007; Grzywacz et al. 2014a). It remains to be seen if truly large-scale market penetration can be achieved in these regions with the existing generation of products. Australian growers have incorporated BV for management of *H. armigera* in field crops, and importation of *Helicoverpa zea* NPV (HezeSNPV) for *H.armigera* control is now supplemented by local sources of a HearSNPV isolate (Buerger et al., 2007; Hauxwell et al., 2010). A major breakthrough in adoption of BV by producers was bringing together new midge resistant sorghum hybrids with HearSNPV to produce an IPM system that controlled the two major crop pests alongside local production of the BV (Franzmann et. al., 2008). HearNPV, SpltNPV and SeMNPV are registered in Thailand and Vietnam, though supply currently appears to depend on imports and public sector suppliers rather than local commercial sources (Nakai and Cuc, 2005; Ratanastien et al., 2005; Skovmand, 2007). In South America, Brazil leads BV development with a well-established program for production and use of *Anticarsia gemmatalis* NPV (AngeMNPV) for control of velvet bean caterpillar on soy (Moscardi, 1999; 2007; Sosa-Gómez et al., 2008). More recently, production and use of AngeMNPV has begun in Mexico (Williams et al., 2013a). The production of AngeMNPV was initiated in Brazil as a public sector project but commercial producers subsequently were brought in to scale up production. Mass-reared insect production was later introduced in Brazil to supplement the original field-based production system when the treatment areas rose to 2 million ha in 2004 (Moscardi, 2007). However, since the use of no-tillage systems involving the routine prophylactic use of broad spectrum insecticides in place of BV applications have been widely adopted, AngeMNPV is now used on less than 300,000 ha (Moscardi et al., 2011; Panazzi, 2013). The rapid shift in the fortunes of what was a very successful microbial pesticide is an illustration of the dynamic nature of modern commercial agriculture and how continued user acceptance of successful microbial pesticides cannot be taken for granted. Despite the decrease in use, this program remains a model for public sector development of a BV that successfully spawned large-scale commercial use. Development of *Spodoptera frugiperda* NPV (SpfrMNPV) for controlling *S. frugi*perda in maize, *Condylorrhiza vestigialis* NPV (CoveNPV) for pest control on poplar trees (*Populus* spp.) and *Erinnyis ello* GV for cassava pest control (Bellotti et al., 1999; Moscardi et al., 2011) is also underway by research institutes in

Brazil, while commercial production of SpfrMNPV and *Autographa californica* MNPV (AcMNPV or AucaMNPV) is also reported in Guatemala, although the scale of use is not clear (Sosa-Gómez et al., 2008). Efforts continue to extend the use of the successful potato tuber moth *Phthorimaea operculella* GV (PhopGV), currently produced in Bolivia by the public or non-government organization (NGO) sector (Sporleder, 2003; Kroschel and Lacey, 2008; Sporleder and Kroschel, 2008; Lacey and Kroschel, 2009) for both field crop (Wraight et al., 2007b; Arthurs et al., 2008c; Sporleder and Kroschel, 2008; Sporleder and Lacey, 2013) and stored product use in North and South America (Arthurs et al., 2008b, Sporleder and Kroschel, 2008; Lacey et al., 2010a; Sporleder and Lacey, 2013). Studies have also focused on the formulation of PhopGV (Sporleder, 2003; Arthurs et al., 2008b) and its propagation *in vivo* (Sporleder et al., 2008) for control of the pest host. In some areas of South America, a new potato pest, *Tecia solanovora,* has supplanted *P.operculella* as the main potato pest, threatening the efficacy of PhopGV in potato stores. The identification of a new strain of PhopGV showing activity against both pests is particularly promising; without such dual activity, farmer use is likely to decline precipitously as *T. solanovora* spreads (Gómez-Bonilla et al., 2011).

One of the most widely used commercially developed viruses is the codling moth, *Cydia pomonella* granulovirus (CpGV). Although CpGV was developed and commercialized for use in Europe in 1987 (Hüber, 1998; Cross et al., 1999; Vincent et al., 2007), it was registered in North America more recently (Vincent et al., 2007; Lacey et al., 2008b) and is now used worldwide (Lacey et al., 2008b; Sosa-Gómez et al., 2008). A comprehensive review of the CpGV literature by Lacey et al. (2008b) concluded that CpGV provides good codling moth population control. Other reasons for its widespread adoption are that no spray interval is required throughout the growing season and before harvest,, and it is safe for applicators, the food supply and non-targt organisms. Although it is widely used in Europe and in North America, adoption by conventional growers is still limited compared to organic growers. The principal caveat for its use is the relatively low persistence of the virus due to solar degradation, necessitating frequent re-application when codling moth pressure is high. Indeed, given the issue of its low persistence in the field, its relatively successful use by the apple industry is an interesting illustration that even products with less than optimal performance can succeed under the right circumstances. It may well be that if application can be timed to coincide with peak fruit entry by first instar coddling moth larvae and the BV can rapidly infect a high proportion of larvae before significant damage occurs, adequate control can be achieved even in a context where the BV has low persistence (Cherry, 2000; Grzywacz et al., 2008). Another factor in CpGV's favor is high virulence and the ease and speed with which it infects (Ballard et al., 2010a). Pest ecology may be another element; in many apple growing systems there are only one or two pest generations per year and growers can target the early larval stages with a high degree of confidence, ensuring that even a short lived virus can achieve acceptable control (Lacey and Shapiro-Ilan, 2008). It must also be noted that CpGV is not a stand-alone product in apple production but a component in a well-developed "soft" IPM system (Lacey et al., 2008b). BVs like other biological control agents (BCA) may perform best as part of a comprehensive IPM system rather than as chemical substitutes (Lacey and Shapiro, 2008). The success of soft IPM in apples also may be related to the long duration of tree crop systems that facilitate the successful establishment of natural enemy complexes, a situation less common in annual crops. Another issue may be that the relatively high profile and consumer demand for "organic apples" provides an additional market incentive to enable biological insecticides such as CpGV to capture a significant market niche.

Expansion of BV use is not without potential problems. Following widespread adoption of CpGV in parts of Europe, extremely high levels of resistance have been reported in certain locations where it has been used for 20 years or more (Fritsch et al., 2005; Eberle and Jehle, 2006; Sauphanor et al., 2006; Zichová et al., 2013). Laboratory studies reveal that rapid development of extreme resistance (100,000 resistance ratio) is possible due to sex-linked inheritance of a dominant resistance gene (Asser-Kaiser et al., 2007) and involves a specific mutation affecting an early block on virus replication (Asser-Kaiser et al., 2011). It has been shown that this resistance can be overcome by using BV products containing different CpGV isolates than the original Mexican strain used in all earlier CpGV products (Eberle et al., 2008), and a number of new products incorporating the new CpGV isolates have now been brought to market (Zichová et al., 2013; Andermatt Biocontrol, 2014). However, to ensure future sustainability, an integrated approach that alternates other soft interventions with CpGV products is recommended when the virus is used extensively within a region (Lacey et al., 2008b). An interesting contrast with *C. pomonella* resistance is use of AngeMNPV in Brazil. Despite the ease with which resistance to AngeMNPV can be selected for in laboratory populations of *A. gemmatalis* (Abot et al., 1997) and the extensive use of AngeMNPV over many years, no reports of field resistance to AngeMNPV have been confirmed (Moscardi, 2007). This contrast may indicate that widespread geographical use of a virus is less a factor in selecting resistance than reliance on a single genetic strain. If so, producers of BV products should plan to incorporate either a wild type mixture of strains in a product or have alternate strains developed and available as part of a product resistance management strategy.

The appearance of a commercial GV product against false codling moth, *Cryptophlebia leucotreta,* in South Africa is an important step as the first commercially available BV produced in Sub-Saharan Africa (Singh et al*.,* 2003; Moore et al., 2004a). Another BV that has been under active development in Africa is the NPV of S*podoptera exempta* NPV (SpexNPV) for control of the African armyworm, a major migrant pest in Africa (Grzywacz et al., 2008). A pilot production plant was set up in Kenya by a private commercial producer (Van Beek, 2007) and a HearNPV product from this producer was registered in Kenya and Ghana in 2012; however, the scale of use is unclear. Diamond back moth, *Plutella xylostella*, is another global pest that has been a priority target for research of both *P. xylostella* GV (PlxyGV) and *P. xylostella* NPV (PlxyMNPV) (Kariuki and Macintosh, 1999; Grzywacz et al., 2004). A comparison of PlxyGV and PlxyMNPV showed that both had similar pathogenicity on the basis of OB counts but that PlxyGV infections produced many more OBs per unit of host weight (Farrar et al*.,* 2007). Commercial PlxyGV products are available in China though the scale of use is uncertain (Yang, 2012).

Turfgrass pest control has also been a focus for pests such as *Agrotis ipsilon* using an NPV (AgipMNPV, Prater et al., 2006). Much of the work involves protecting golf course turf, but while AgipMNPV can give good control of early instars, its persistence is limited by frequent mowing. Additionally, exposure to UV reduces secondary cycling of the virus (Bixby-Brosi and Potter, 2010). BV isolates under development by the public sector (Table 1) have not yet attained product status.

Research on expanding use of other existing BV products continues, including the use of *Spodoptera exigua* NPV (SeMNPV) in glasshouses in southern Europe (Lasa et al., 2007). An interesting development is the commercialization in Japan of a joint formulation of *Adoxophyes orana* GV and *Homona magnanima* GV for controlling two tortrix pests of tea (Kunimi, 2007).

The use of BV in forest insect pest control in North America and Europe, a traditional focus of BV research (Cunningham, 1995; Martignoni, 1999; Podgewaite, 1999), has remained limited. The development of some forest pest BV, such as the gypsy moth NPV has continued (Cadogan et al., 2004; Moreau and Lucarotti, 2007) and commercial production of sawfly *Neodiprion abietis* is now also underway (Lucarotti et al., 2007). The lack of expansion of BV use in forest pest control may reflect the preferential adoption of *Bacillus thuringiensis*-based products, with their ready availability and wider host range (Moreau and Lucarotti, 2007; van Frankenhuyzen et al., 2007), rather than rejection of BV microbial pesticides. In Asia a number of forest pest BV are either in production or use in China, Japan and India; the scale of use remains unclear, although probably limited (Nair et al., 1996; Peng et al., 2000; Kunimi, 2007; Sun and Peng, 2007; Yang et al., 2012). Use of BV in stored products has also been a focus of research, particularly on *Plodia interpunctella* GV (PlinGV) (Vail et al., 1991, 1993). PlinGV has shown promise for control both through direct action and auto-dissemination but as yet has not been commercially developed.

2.2 Research issues that constrain expansion of the use insect viruses

Mass production of BV at a cost most potential users can bear remains a significant issue. Production of commercial BV insecticides is still dependent on *in vivo* systems utilizing specially reared or wild collected insects (Reid et al., 2014; Grzywacz et al., 2014b). *In vivo* systems for production of BV in live larvae remain the normal production method for commercial companies and for public sector programs (Moscardi, 1999; Van Beek and Davies, 2009; Grzywacz et al., 2014a) but the relatively high cost of producing BV in living insects compared to their chemical insecticide counterparts remains a constraint as farm prices are difficult to reduce below \$20 per ha and scaling up in vivo BV production with its demands for high quality disease-free insects is also a challenge (Reid et al., 2014). The use of automation and mechanization in inoculation, rearing, and harvesting has facilitated mass production and made BV a viable commercial option for the current range and usage scale. However, this manufacturing approach remains unattractive to many companies in North America and Europe that are unfamiliar with mass insect culture as a mainstream production technique, and while, the *in vivo* production approach remains capable of meeting the current market needs, the ability to produce the amounts of BV needed for large scale field crop protection is far from certain. It remains to be seen if the recent sharp decline in the use of AgMNPV in Brazil after a major investment in laboratory-based mass production facilities (Moscardi et al., 2011; Panazzi, 2013) will have a significant impact on the willingness to fund a major expansion of *in vivo* BV production.

While most viral pesticides are produced in specialized facilities, field production *in vivo* has been a viable approach for a few commercial BV products such as AgMNPV in developing countries (Hunter-Fujita et al., 1998; Moscardi, 2007; Alves and Lopes, 2008). Field production is planned for SpexNPV in Africa (Grzywacz et al., 2014b), although large scale commercial viable mass production has yet to be successfully established for any BV other than AgMNPV.

Facing future needs for large-scale mass production of BV, in vitro cell culture remains a major approach to overcoming supply and cost constraints that limit BV use (Black et al., 1997, Moscardi et al., 2011). Mass production of hosts to produce viruses has been under development for 30 years but has not yet been successfully scaled up to the levels required to meet commercial acceptability (Granados et al., 2007). While many cell lines capable of supporting BV replication exist, the cells are relatively fragile compared to the bacterial and yeast cells normally used in large scale cell culture systems. Meeting commercial needs for BV production would require bioreactors of >10,000 l that are capable of continuous high efficiency production. (Black et al., 1997, Reid et al., 2014). Successful insect cell production has been reported in a number of different bioreactors but only at volumes of 20- 600 l (Reid et al 2014). Besides developing large-scale reactors suitable for insect cell lines, *in vitro* systems require low cost chemically defined media optimised for insect cell production to be cost effective and this is also not yet available. BV production quality also has been an issue; in particular, low cell yield and the maintenance of acceptable phenotypic qualities are constraints yet to be overcome (Pedrini et al., 2006; Nguyen et al., 2011). Thus, while research to develop cost effective *in vitro* systems continues (Granados et al., 2007; Szewczyk et al., 2006; Moscardi et al., 2011), there are as yet no indications that commercial production will begin in the near future, though technical and commercial “road maps” for such a ventures have been developed (Reid et al., 2014).

The slower killing speed of BV compared with most synthetic insecticides remains a significant barrier to their wider adoption (Copping and Menn, 2000; Szewcyk et al., 2006). Speed of action remains an important factor in selecting strains because faster acting strains would reduce crop damage and would be more attractive to users accustomed to the rapid kills obtained with many, though not all, chemical pesticides. A major focus of applied research to increase speed of action has been genetic modification (GM) of BV to insert or delete genes that quickly initiate cessation of feeding and accelerate death. The inserted genes include insect specific toxins from the scorpions *Androctonus australis* and *Leiurus quinquestriatus*, the spider *Tengeneria agrestis*, the itch mite *Pyemotes tritici* and juvenile hormone esterases (Burdan et al., 2000; Bonning et al., 2002; Szewcyk et al., 2006). Despite promising field trial results, commercial development of these GM BVs appears to have stalled, perhaps because the recombinants produce poor yields in current *in vivo* systems or because the climate of public opinion and regulatory barriers are not sufficiently favorable to GM products in major potential markets such as the EU (Black et al., 1997; Glare et al., 2012).

The adoption of new natural mutant virus strains such as non-liquefying SfMNPV (Valicente et al., 2008) is another route for improving the cost effectiveness of BV that would not face such perceptual or registration barriers; however, the use of a natural faster-acting strain in practice may not be without drawbacks. A faster killing strain of *S. frugiperda* NPV (SpfrMNPV) was identified, but it was found to produce fewer OBs than the slower killing isolate, an evolutionary trade-off that is probably common and could reduce the impact of secondary cycling (Behle and Popham, 2012). Thus, despite extensive research in genetic modification to overcome some of the recognized BV constraints of restricted host range, slower action, and sensitivity to UV, no BV recombinant products with improved performance have been marketed nor do they seem likely to be in the near future. This is partly due to the technical failure to develop recombinants with the desired characteristics but may also reflect the rising costs of registering and deploying GM technology. In addition, recently published research on the genetic and genomic aspects of BV (with 43 genomes sequenced) has thrown an interesting light on BV relationships and evolution (Jehle et al., 2006; Eberle et al., 2009; Herniou et al., 2012).

It has been hoped that genomic data would assist the development of products with improved efficacy, host range, etc. (Inceoglu et al., 2006), but as yet there has been no commercial impact. While generally OBs are stable, they are sensitive to UV inactivation as well as phytochemical degradation on some plant species (Cory and Hoover, 2006; Cory and Evans, 2007: Behle and Birthisel, 2014). Specific phytochemical mechanisms that interfere with BV infectivity on crops have been identified in cotton (Hoover et al., 1998; Hoover et al., 2000) and, more recently, in chickpea (Stevenson et al., 2010). The low persistence of BV on these and other crops is still perceived as a real limitation to the current generation of BV microbial pesticides (Copping and Menn, 2000; Moscardi et al., 2011; Behle and Birthisel, 2014). However, given the relative commercial success of CpGV, which has a short persistence time due mainly to solar inactivation, limited persistence may not be an insurmountable barrier to adoption provided products give a degree of control that meets the users core requirements.

BV can be applied using any commercial spraying system without special formulation (Gan-Mor and Mathews, 2003), although stickers, gustatory stimulants and UV protectants are often routinely incorporated into tank mixes to improve efficacy (Burges and Jones, 1998; Behle and Birthisel 2014). Effective application rates for field use of NPV species that contain multiple virions vary between 0.5-5 x 10^{12} OBs per ha (Moscardi, 1999), while for the GV with only one virion per occlusion body, rates can be higher (Moscardi, 1999). Research into new technology for applying BV seems to have advanced little in recent years, perhaps in recognition that farmers' decisions on the acquisition and use of sprayers is not likely to be driven to any significant extent by their specific ability to deliver microbial agents such as BV. There is now more interest in using precision application technologies for crop protection. In the next decade, use of minimal or precisely applied inocula in place of the traditional blanket spraying may be one of the most interesting avenues for exploiting BV more successfully and overcoming issues of cost and availability.

In addition to improving speed of kill, efficacy, host range, and persistence, applied research on formulation of BV remains one of the most important routes to BV product improvement (Burges and Jones, 1998; Behle and Birthisel, 2014). However, published research on this issue is very limited, probably due to proprietary issues, so it is unclear if limited publications reflect lack of significant progress. A number of improvements have been reported but it is not clear if advances are likely to appear in products in the near future. Most virus products are produced and sold as suspension concentrates, wettable powders and granules.

A minimum shelf life of 18 months was recommended over 30 years ago (Couch and Ignoffo, 1981) and some products are now available that meet this standard (Burges and Jones, 1998; Lacey et al., 2008b); these usually include adjuvants that stabilize the virus and improve suspension in water. Factors that affect shelf life of viruses (temperature and formulation components) have been reported for the NPV of the celery looper *Anagrapha falcifera* (AnfaMNPV) (Tamez-Guerra et al., 2000; Behle et al., 2003) and CpGV (Lacey et al., 2008a).

Some producers ship virus as frozen product and advise keeping the virus frozen until used, although this may not always be possible under operational conditions. Freezing is not essential to preserve BV, which can remain active in purified suspensions over long periods, even at room temperature. However, refrigeration or freezing does appear to be necessary to prevent the loss of activity related to the proliferation of contaminant bacteria and the oxidation of host derived lipids (Burges and Jones, 1998) and, thus, maintain the infectivity of mass produced suspensions (Lasa et al., 2008). The need for cold storage of BV is less of constraint in glasshouse and protected crops where use of biological control agents such as predators and parasitoids, requiring special storage or immediate use on receipt, has become increasingly common. It does, however, limit adoption in many field crops where biological control agents are less widely utilized.

The wider availability of formulations with ambient shelf life comparable to synthetic pesticides (> 2 years) would be a substantial stimulus for expansion of BV use. Air-dried, spray-dried, and freeze-dried formulations have been widely studied with promising results for storage stability and activity (Alcázar et al., 1992; Tamez-Guerra et al., 2000, 2002; McGuire et al., 2001; Behle et al., 2003; Arthurs et al., 2008b). Spray drying of AnfaMNPV did not significantly reduce activity of lignin formulations over 6 months storage at 4°C (Behle et al., 2003). Freeze dried formulations of the PhopGV were comparable in activity to emersion in an aqueous virus suspension (Arthurs et al., 2008b). Freeze dried and microencapsulated formulations of HearSNPV were also found to be as effective in the field as aqueous suspensions when applied on chickpea (Cherry et al., 2000). However, AnfaMNPV spray-dried formulations were reported to have higher residual activity compared with a commercial glycerin-based formulation (Behle et al., 2003). Differences in results may relate to specific crop-pest factors such as chemical inactivation reported on chickpea, so formulations may need to be tailored in some cases to the specific crop (Stevenson et al., 2010). Encapsulation of viral OBs in lignin via spray drying has been developed and tested with MNPV and GV and produced higher mortality and longer persistence than unformulated controls (Tamez-Guerra et al., 2000; McGuire et al., 2001; Behle et al., 2003; Arthurs et al., 2006; 2008a, Behle and Popham 2012). Castillejos et al. (2002) reported considerably greater persistence with a granular phagostimulant formulation of the SfMNPV than with an aqueous suspension. In contrast, the commercially produced particle films and waxes, marketed as sunburn protectants for fruit are reported as providing no significant additional protection for CpGV (Lacey et al., 2004; Arthurs et al., 2006; 2008a).

A principal concern of growers is the need for frequent reapplication of BV due to rapid inactivation when exposed to sunlight (Behle and Birthisel, 2014). BV are especially sensitive to the ultraviolet spectrum (Ignoffo, 1992; Burges and Jones, 1998; Tamez-Guerra et al., 2000; Lacey and Arthurs, 2005), although specific host plant phytochemical factors can also contribute to low persistence on some crops and tree species (Cory and Hoover, 2006). The relative role of low UV persistence in constraining BV product use varies significantly due to a complex of biotic and abiotic crop specific factors such as UV levels, crop architecture, pest infestation patterns and cropping practices (Stevenson et al., 2010). In tropical crops exposed to high UV, persistence of BV can be less than 24 hours; but persistence of other microbial pesticides such as Bt and even chemicals can also be short on these crops due to the combination of high UV and high temperature, which drives inactivation, chemical breakdown and volatization (Cherry et al., 2000).

One issue complicating the evaluation of research on UV persistence is the variability of experimental protocols used by different researchers. Some researchers evaluate natural sunlight exposure, which also has issues of variability, but many studies use various artificial UV sources that may not closely mimic natural sunlight spectra or leaf surface exposure. Exposure distances and duration vary and the choice of substrate can be a confounding issue. For example, direct heating effects may confound the effect of UV exposure when substrate temperatures are not restrained within environmentally valid bounds. Optical brighteners (Tinopal, Blankophor P167, and other stilbene derivatives), with and without titanium dioxide, have been shown to increase the persistence of NPV and GV (Farrar et al., 2003; Monobrullah and Nagata, 2001; Sporleder, 2003). However, Sajap et al. (2009) found that, although adjuvants such as Tinopal gave significantly improved UV protection in laboratory studies of SpltMNPV, in subsequent field trials on brassicas, no clear advantage was conferred over unformulated SpltNPV. A number of other materials that absorb specific wavelengths, including specialized dyes, chemicals and natural substances such as lignin sulfate, polystyrene latex, Congo Red, green tea, antioxidants, iron oxide and others have been tested to improve the residual activity of entomopathogenic viruses (Burges and Jones, 1998; Charmillot et al., 1998; Ballard et al., 2000b; de Morães Lessa and Medugno, 2001; McGuire et al., 2001; Sporleder, 2003; Asano, 2005; Arthurs et al., 2006; Shapiro et al., 2008). Molasses, sucrose and skimmed milk powder have also been reported to slightly improve persistence of CpGV (Charmillot et al., 1998; Ballard et al., 2000b). Alves et al. (2001) demonstrated greater persistence of NPV in an oil emulsion formulation than in a wettable powder for control of *A. gemmatalis*. UV protected petroleum spray oils were also found to be effective with HearSNPV (Mensah et al., 2005). In considering formulations that improve UV stability, it is not only performance that should be taken into account. Some experimentally demonstrated formulation additives have not been adopted for commercial use due to factors such as high cost, phytotoxicity, storage incompatibility, cosmetic unacceptability on fresh produce, or because application at the required concentrations, is impractical due to high viscosity or blocking of spray filters as occurs with some particulate additives.

It has been suggested that the success of HearNPV in Australia is related to very rapid acquisition, mitigating the problem of low BV persistence on crops (Murray et al., 2001), although the use of additives in tank mixes to improve efficacy of HearNPV is also an important factor in its success (Mensah et al., 2005; Hauxwell and Reeson, 2008). Increasing the attractiveness of spray deposits by adding attractants and feeding stimulants to tank mixes has shown promise in accelerating the acquisition of virus; for example, molasses is reported to be one of the most effective feeding stimulants for codling moth larvae (Ballard et al., 2000b). Other phagostimulants with potential for improving efficacy of CpGV include monosodium glutamate (Pszczolkowski et al., 2002) and trans-1-aminocyclobutane-1,3-dicarboxylic acid (trans-ACBD) (Pszczolkowski and Brown, 2004). However, use of high concentrations of additives such as molasses may have unacceptable side effects such as stimulating disfiguring fungal growth such as sooty mold on fresh produce. Schmidt et al. (2008) reported significant improvement of CpGV used in conjunction with the pear ester larval and adult attractant kairomone. However, Arthurs et al. (2007) reported inconsistent results in similar tests on apple and pear, and suggested that more practical improvements in formulation and application strategies were needed. Knight and Witzgall (2013) reported significant increases in larval mortality when combining any one of three yeasts, *Metschnikowia pulcherrima*, *Cryptococcus tephrensis* or *Aureobasidium pullulans,* with CpGV compared with CpGV alone. A field trial confirmed that fruit injury and larval survival were significantly reduced when apple trees were sprayed with CpGV, *M. pulcherrima* and sugar.

Wetting and sticking surfactants are generally recommended to improve mixing, reduce surface tension and increase deposition over plant surfaces (Burges and Jones, 1998). The use of additional stickers with entomopathogenic viruses was reported by Ballard et al. (2000), Tamez-Guerra et al. (2000) and Arthurs et al. (2008a). Optical brighteners have also been shown to enhance the infectivity of a number of NPV species, a response related to effects on the peritrophic membrane (Morales et al., 2001; Murillo et al., 2003; Martinez et al., 2004; Farrar et al. 2005; Toprak et al., 2007). Similarly, Cisneros (2002) demonstrated a synergistic effect of 1% borax on activity of SfMNPV. Formulation research has not yet produced significant impacts on the overall performance of commercial BV products, but the availability of formulations with substantially improved persistence would improve product attractiveness for many crop systems.

The use of other additives to enhance the efficacy of BV infection has been widely explored. The enhancins are a group of viral proteins recognized to increase both NPV and GV viral potency in heterologous hosts and suggest significant potential to expand the host range of specific BV (Slavicek, 2012), although these have not yet been developed for commercial use. Azadaractin and other neem-derived chemicals also have been reported to effectively reduce the

BV dosage needed to control pests in bioassays (Zamora-Aviles et al., 2013), and if validated in the field, could prove useful in lowering the cost of product.

The impact of expanded GM crop production on the use of BV remains to be determined. While the adoption of insect resistant GM crops can remove established markets for BV in some crops such as cotton (Buerger et al., 2007), it may also present opportunities for incorporating BV into GM cropping systems to cope with secondary non target pests, or as part of an insect resistance management strategy (Thakore, 2006; Kennedy, 2008). HzNPV significantly improved control of *H. zea* in GM sweet corn, although not as consistently as application of the insecticide spinosad (Farrar et al., 2009). Research on the use of insect virus genes in transgenic plants as a new source of insect resistance may, in the long term, provide the capability to utilize BV in crop protection (Liu et al., 2006).

While BV may be deployed using basic strategies of inoculation, conservation or augmentation, in current practice, BV is applied augmentatively as a microbial pesticide on an "as needed" basis. In the opinion of some researchers, however, pesticidal use is a barrier to realising the full potential of biological agents and their ability to replicate, persist and spread (Waage, 1997). An alternative to conventional spray application is dissemination of BV formulations via novel lure and contaminate technologies incorporating pheromones (Vega et al., 2007). Adult insects attracted to BV inoculum become surface contaminated and pass the virus to egg surfaces and subsequently to hatching larvae. This strategy has been recently applied to orchard pests (Cross et al., 2005); other examples are presented by Vega et al. (2007).

Despite the recognized importance of secondary cycling via horizontal and vertical transmission of BV in pest populations, there has been little deliberate exploitation of BV capacity to replicate and cycle in the way that specific inoculation strategies are used for *Oryctes* virus (Jackson et al., 2005) or cropping practices designed to promote BV conservation (Moscardi, 1999; Cory and Evans, 2007). Virus ecology remains a very active field of research for both crop and forest pests (Cory and Myers 2003; Fuxa 2004; Harrison and Hoover 2012), expanding our knowledge of BV epidemiology and virus host population dynamics. Studies have included secondary cycling, horizontal and vertical transmission, and the interaction of BV with other pathogens such as *Wolbachia* (Graham et al., 2010) and offer interesting insights into how BV effectiveness might be enhanced in the field through biotic interactions. Although the research has not yet been exploited in terms of improving our use of BV on most crops, the ecology of host pathogen interactions is envisioned to be a way forward to developing new strategies for novel BV deployment (Waage, 1997).

2.3 Societal factors and their role in determining the adoption of insect viruses

Environmental pressures and consumer health concerns have been increasingly focused on the health and environmental impacts of crop protection products and the well-established safety of BV (OECD, 2002; Leuschner et al., 2010; Mudgal et al., 2013) is a major advantage. While public surveys have not shown that food safety risks are perceived as a major concern, they are a significant issue for up to 25% of consumers (Food Standards Agency 2013). The recent controversy over neonicotinoids in the EU has shown that public concerns can drive significant changes in crop protection policy even if the scientific evidence is controversial (Gross 2013). These concerns in the EU have led to the sustainable use directive (SUD), a policy of reducing reliance on chemical pesticides and mandatory adoption of integrated pest management (IPM) for all crops (Hillocks 2012) . In addition, chemical pesticides must be reregistered, which has led to a reduction in the number of chemical crop protection products allowed from approximately 1,000 in 1993 to less than 330 today (European Commission 2009). These measures are undoubtedly increasing the potential for use of BV; however, increased demand for new BCA elicit serious concerns that the supply of new products remains inadequate to replace the chemical pesticides being withdrawn (Hillocks 2012).

One barrier to increasing the supply of commercial BV products is registration (Chandler et al 2011; Ehlers 2011; Lapointe et al., 2012). Regulatory authorities in many countries and jurisdictions are unable to complete registration of BV products in a timely, economic and transparent manner (Kabaluk, 2010; Gwynn, 2014). This may be due to bureaucratic inertia in some cases, but often the absence of the appropriate biological expertise among regulators has been cited as a significant constraint (Chandler et al., 2011). Some regulatory bodies such as the US EPA as appear to be proactive in developing the appropriate expertise and a positive ethos to facilitate the registration of new BV products through effective fast track systems (Bailey et al., 2010) but the EU, although sponsoring active reviews of microbial pesticide registration (Ehlers 2011), has not yet implemented a specific fast track for microbial pesticides. EU registration has long timelines and higher costs that deter registrations, especially by the small-medium size enterprises (SMEs) that are frequently in the forefront of microbial pesticide innovation and develop 80% of novel microbial pesticide products (Chandler et al., 2011; Ravensberg, 2012). The use of microbial pesticides has not yet generated serious public concern, although the issue has been mentioned by some authors such as Lapointe et al. (2012), attitudes may change as BV use expands.

2.4 *Insect viruses in the next decade*

There is a clear need for need for new BV products active against pests that may increase in impact as chemical actives are withdrawn. Most BV products recently commercialised or being brought to market are based on species that are well known and have been studied for at least 30 years. There is a serious concern about the dearth of novel BV species. Given the limited progress since 2001 in identifying new BV, it is far from clear that new crop protection products will emerge without increased funding for research and development of BV against new and emerging threats arising from chemical withdrawal. There is also a need for new technology to mass-produce BV at costs that appropriate for large-scale use of BV in field crops. Although *in vivo* production is an established technology, it is far from certain that it can be expanded to meet the quantum leap in production that is needed to replace chemical pesticides for major field crops. It remains to be seen if *in vitro* systems will overcome the scaling up cost and quality issues that have prevented these from be adopted by commercial producers. The other key need is to develop a better understanding of how BV interact with other BCA to identify synergys that can enhance their overall performance. Many believe that the BV, like other BCA, will never achieve their full potential until they are deployed as components of ecologically based IPM systems rather than substitutes for chemical insecticides.

3. Entomopathogenic Bacteria

3.1 Bacillus thuringiensis (Bt)

3.1.1 Background and overall status. An enormous number of bacterial species have been reported from pest and beneficial insects (Jurat-Fuentes and Jackson, 2012) but a relatively small number of entomopathogenic bacteria have been commercially developed for control of insect pests of crops, forests, turf, humans, and livestock. These include several *Bacillus thuringiensis* (Bt) sub-species, *Lysinibacillus (Bacillus) sphaericus, Paenibacillus* spp. and *Serratia entomophila* (Table 2). The most widely used bacteria for control of numerous insect pests are Bt subspp. (Glare and O'Calaghan, 2000; Federici, 2005; Bravo et al., 2011; Glare et al., 2012; Jurat-Fuentes and Jackson, 2012).

Highlights of the history and commercial development of Bt are presented by Beegle and Yamamoto (1992), Federici (2005) and Davidson (2012). Sub-species represent about 98% of formulated sprayable bacterial microbial pesticides, due in part to the wide host range with activity against Lepidoptera, Diptera (Nematocera), Coleoptera (Chrysomelidae and Scarabaeidae), additional species in other orders of insects and other pest invertebrates (mites and nematodes) (Carneiro et al., 1998; Schnepf et al., 1998; Wei et al., 2003; van Frankenhuyzen, 2009). Three notable examples are Bt strains with activity for scarab larvae (Bt subsp. *japonensis* (Buibui strain), Suzuki et al., 1992); two sawfly species *Diprion pini* and *Pristiphora abietina* (Porcar et al., 2008); and root knot nematodes, *Meloidogyne* spp. (Chen et al., 2000; Li et al., 2008; and Khan et al. 2010).

Additional prospection and development will most likely provide *B. thuringiensis* isolates with an even broader spectrum of activity. Crickmore et al. (2014) provide a continually updated list of Bt toxins with links to information on additional host insects and other organisms that are susceptible to them. There are currently no less than 73 families of crystal (CRY) toxins comprising a total of 732 toxins, 3 families of cytotoxic (Cyt) proteins including 38 different toxins and 125 Vegetative Insecticidal Proteins (VIPs) belonging to 4 different families (Crickmore et al., 2014).

The primary reason for the utilization of Bt is that it combines advantages of chemical pesticides and microbial pesticides. Like chemical pesticides, Bt is fast acting, easy to produce at low cost, easy to formulate, and has a long shelf life. It also can be applied using conventional application equipment and systemics (i.e. in transgenic plants). Unlike broad spectrum chemical pesticides, *B. thuringiensis* toxins are selective and negative environmental impact is very limited (Glare and O'Callaghan, 2000; Lacey and Siegel, 2000; Hokkanen and Hajek, 2003; Lacey and Merritt, 2003; Birch et al., 2011).

3.1.2 Control of pest insects with B. thuringiensis microbial pesticide products

3.1.2.1 Crops and orchards: Bt has no pre-harvest spray interval and can be applied until harvest begins. It has minimal or no impact on beneficial organisms in these agroecosystems; however, although efficacious, it is sensitive to solar degradation and requires frequent application.

B. thuringiensis subsp. *kurstaki* (Btk, Dipel) and to a lesser extent *B. thurinigiensis* subsp. *aizawai* (Xentari) are used for control of lepidopteran pests in orchards and in vegetable production (Glare and O'Callaghan, 2000; Lacey and Shapiro-Ilan, 2008; Glare et al., 2012). It is used extensively in organic vegetable production and is increasingly being utilized by conventional growers. Control of a plethora of pest Lepidoptera is common in row crops including crucifers, solanaceous vegetables, cucurbits, corn, legumes, soybeans, cotton, and others. The implementation of Btk for control of orchard pests, particularly leafrollers and other defoliators, was described by Lacey et al. (2007) and Lacey and Shapiro-Ilan (2008).

A multitude of papers on applied research and use of Bt-based products for protection against lepidopteran pests of vegetables and tree fruit have been published since 2000 and many are referenced by Glare and O'Callaghan (2000), Metz (2003), Lacey and Kaya (2007), Jurat-

Fuentes and Jackson (2012). Kabaluk and Gazdik (2005) provide a directory of biopesticides that includes producers of several commercial Bt products for control of Lepidoptera.

Control of coleopteran pests in crops using commercially produced *B. thuringiensis* is limited to beetles in the family Chrysomelidae, principally the Colorado potato beetle, *Leptinotarsa decemlineata* (Wraight et al., 2007b, 2009). The beetle-active toxin (Cry 3Aa) is produced by *B. thuringiensis* subsp. *tenebrionis* (Btt). It can provide an effective means of control, especially when applied at regular intervals against early instars. Btt was rapidly developed as a microbial pesticide in the late 1980s and early 1990s (Gelernter and Trumble, 1999; Gelernter, 2002). However, several factors, most notably competition with neonicotinyl insecticides, resulted in its near disappearance from the marketplace (Gelernter, 2002). The Cry3Aa toxin expressed in transgenic potato provides complete protection from *L. decemlineata* but current public opposition to transgenes in food has resulted in removal of transgenic potato from the market in North America and Europe. Transgenic ‘Spunta’ potato lines with the *cry1Ia1* gene were completely resistant to potato tuberworm in laboratory and field tests (Douches et al., 2002, 2011).

3.1.2.2 Stored product pests: Several pest insects attack stored grain, fruit, nuts, potatoes and other stored food products. Btk products have been used to control several of these pests (Lord et al., 2007; Shapiro-Ilan et al., 2007; Kroschel and Lacey, 2008). Good efficacy of Btk has been demonstrated and protocols have been published for the evaluation of Btk control against *Plodia interpunctella* and other lepidopteran pests of stored grain (Lord et al., 2007). Despite the massive volume of grain in grain silos, only the top 10 cm of grain require treatment (Lord et al., 2007). Kroschel and Lacey (2008) and Lacey and Kroschel (2009) described examples of large-scale implementation of Btk in several countries for control of the potato tuber moth, *P.operculella* in rustic stores of potato tubers.

3.1.2.3 Forests: Btk is the principal non-chemical means of control for lepidopteran pests of forests and development in the 1970s and 1980s facilitated broader commercial development in the 1980s and 1990s (van Frankenhuyzen et al., 2007). Btk has been used extensively against the spruce budworm, (*Choristoneura fumiferana*) and gypsy moth (*Lymantria dispar*) (van Frankenhuyzen et al., 2000; Bauce et al., 2004; van Frankenhuyzen et al., 2007). Protocols for the evaluation of Btk and other isolates of Bt for control of *C. fumiferana* and *L. dispar* are presented by van Frankenhuyzen et al. (2007). Btk has also been used for control of other lepidopteran forest defoliators across North America and Europe including *Thaumetopoea processionea, T. pityocampa, Lymantria monacha, Dendrolimus sp. Bupalus piniaria, Panolis flammea, Tortrix viridana, Operophtera brumata, Dioryctria abietella, Lambdina fiscellaria fiscellaria, Choristoneura occidentalis, C. pinus pinus, Orgyia leucostigmata, O. pseudotsugata*, and others (Fuxa et al., 1998; van Frankenhuyzen, 2000).

The only non-lepidopteran forest pest insects that are susceptible to Bt are in the coleopteran family Chrysomelidae. Bauer (1992) bioassayed Btt for larvicidal activity against the imported willow leaf beetle, *Plagiodera versicolora,* reared on poplar (*Populus*) or willow (*Salix*). Good larvicidal activity of the bacterium was only observed on the larvae reared on poplar. Genissel et al. (2003) reported on the deleterious effects of feeding *Chrysomela tremulae* larvae and adults on leaves from transgenic poplar expressing the *cry3Aa* gene from Btt. No large scale field trials have yet been conducted with Btt for control of chrysomelids in forests.

3.1.2.4 Lawn and turf: Klein et al. (2007) and Koppenhöfer et al., (2012) provide overviews of the use of Bt subspp. for control of turf pests. Btk and Bt subsp. *aizawai* are registered for control of sod webworms and armyworm, *Mythimna* (*Pseudaletia*) *unipuncta,* in turf. Although not widely used for control of these pests, Bt strains provide some control if used when early instars are present and applications are made during the early evening to avoid as much UV degradation as possible. Oestergaard et al. (2006) demonstrated control of the European crane fly, *Tipula paladosa,* with *B. thuringiensis* subsp. *israelensis* (Bti) applied against early instars; however, there are no reports in the literature of routine use of Bti for crane fly control in turf. The Bt subsp. *japonensis* (Buibui strain) is insecticidal for the Japanese beetle, *Popillia japonica*, and other scarab species that are turf pests (Suzuki et al., 1992; Alm et al., 1997; Koppenhöfer et al., 1999, 2012; Bixby et al., 2007). Koppenhöfer et al. (1999) observed an additive and synergistic interaction between entomopathogenic nematodes (*Sterinernema* spp. and *Heterorhabditis bacteriophora*) and Bt subsp. *japonensis* (Buibui strain) for control of the grub *Cyclocephala* spp. An advantage of Bt subsp. *japonensis* over *Paenibacillus popilliae*, another bacterium used for *P. japonica* control, is that it can be grown on artificial media and has a broader host range within the Scarabaeidae.

3.1.2.5 Medically important insects: Several species of culicid mosquitoes (Culicidae) are widespread pests, many of which transmit disease causing agents such as *Plasmodium* spp. (malaria), filaroid nematodes (elephantiasis, Mansonellosis) and viruses (yellow fever, dengue, and several that cause encephalitis) (Foster and Walker, 2009). The aquatic habitats in which Bti is used for mosquito control are extremely diverse in terms of location (salt marsh, tree holes, wetlands, containers, and a variety of other habitats) and water quality (Skovmand et al., 2007).

Black flies (Simuliidae) are always found in lotic habitats (rivers, streams, creeks) (Adler et al., 2004; Adler and McCreadie, 2009) and, in addition to their highly pestiferous activity, some species transmit the filaroid nematodes that cause human and bovine onchocerciasis (Adler and McCreadie, 2009). Bti is the only Bt subsp. that is commercially produced for control of vector and pestiferous Diptera in both the Culicidae (Lacey, 2007; Despres et al., 2011) and Simuliidae (Adler et al., 2004; Skovmand et al., 2007). Although Bti is very efficacious, its persistence in the environment, especially those with high organic content, is short lived and requires frequent reapplication. Dense foliar canopy and rapid settling of toxin in deeper lentic habitats decrease the amount of inoculum reaching the habitat and decreased time for larval exposure. Toxin is carried shorter distances in shallow streams with large substrate to water volume ratios (wide and shallow). Large rivers can result in effective carry of the toxin up to 30 kilometers. Further improvements in formulations and delivery systems are expected to increase efficacy in mosquito and black fly habitats.

3.1.3. Production of B. thuringiensis. The nutrient media and conditions under which Bt and *L. sphaericus* are produced can markedly influence larvicidal activity. Guidelines and typical media ingredients for shake flask, stir tank and deep tank fermentation are presented by Beegle et al. (1991), Lisansky et al. (1993), and Couch (2000). Although there is continued improvement in fermentation technology for *B. thuringiensis*, information on any specific changes in methods and media by industry nearly always is proprietary (Couch, 2000). However, there have been developments in small scale production using unique media components such as local raw ingredients of plant and animal origin and bi-products (such as whey) which provide inexpensive nitrogen and carbon sources for the production of Bt and *L. sphaericus* (Aranda et al., 2000; Lacey, 2007).

3.1.4. Transgenic crops or Bt-crops. The largest market progress over the last two decades was associated with the development of a Bt product different from the microbial pesticides, the Bt transgenic crops. The Cry toxins and VIPs are the only toxins currently used in commercial insecticidal transgenic crops. VIP toxins are only found in transgenics but several Cry toxins produced by Bt-crops are the same as those produced for Bt microbial pestcides such as Dipel or Xentari. GM crops have been the most rapidly adopted production technology in agriculture (Brookes and Barfoot, 2013; James, 2013). Although implementation has not been without controversy, wide acceptance is due to specificity to insects and high efficacy of *B. thuringiensis* Cry toxins, and safety for consumers and non-target organisms (Shelton et al., 2002; Bravo et al., 2011). A large diversity of toxin genes that are relatively simple to clone and express are found in different *B. thuringiensis* strains. The toxin genes are distributed into families that are easy to characterize and the toxins are organized into clearly distinguishable functional domains (Bravo et al., 2007). These traits not only make the mode of action (MOA) of the toxins easier to elucidate but also make both toxins and toxin genes good models for genetic engineering. Early in the 1980's, *B. thuringiensis* was already a commercially successful product. *B. thuringiensis* insecticidal proteins were some of the only gene products meeting the technical and ethical requirements for plant biotechnology. Subsequently, *B. thuringiensis* toxins became the most promising source for development insect-resistant transgenic plants (Kennedy, 2008).

Global Bt-crop acreage has increased enormously in the last two decades, reaching 175 million ha in 2013 (Choudery and Guar, 2010; Brookes and Barfoot, 2013; James, 2013). The adoption rate was 100% or near 100% in 2013 for all major transgenic crops in the primary producing countries. Stabilization of adoption rate and area planted are therefore expected in the coming years (James, 2013).

The increased use of Bt-cotton and Bt-corn has resulted in a significant decrease in the use of chemical insecticides (Phipps and Park, 2002; Brookes and Barfoot, 2013), particularly in cotton (Huanga et al., 2003; Edwards and Poppy, 2009; Krishna and Qaim, 2012). However, transgenic technologies also compete with sprayable formulations of Bt due to the similarity of toxins used and result in a lower commercial share left to Bt microbial pesticides. Furthermore, while reducing the overall market for chemical insecticides, widespread adoption of Bt crops can increase the market for herbicides as new generations of transgenic plants expressing stacked Bt and herbicide-resistance genes are now on the market (James, 2013). Given the widespread environmental concerns over broad-spectrum chemical pesticides, it is possible that GM crops deploying pest specific safe gene products such as Bt toxins may finally be considered a more environmentally acceptable solution for pest control than the development and widespread application of newer chemical pesticides.

Given the high cost of developing and deploying a new transgenic crop, currently estimated as $136 million (McDougall, 2013; Mumm, 2013), it will not be economically viable to develop GM varieties for all crops, including many minor use or locally important crops, or to control all specific pests and diseases (Shelton, 2012). Non-GM crop diversity and local varieties must be maintained for many reasons ranging from differing climates and specific cultural food practices to the need for a diverse genetic base for disease tolerance. Because not all crops and varieties will be transgenic, other conventional but still environmentally friendly means of control must be retained and developed. Among these should be new Bt-based microbial pesticides, as well as other entomopathogen-based pesticides. However, niches for microbial pesticides must address new issues to avoid competition with, for example, focusing on a mosaic of secondary pest problems. Microbial pesticides for forestry and vector control may be an exception to treatment of row crops because competition with trangenics does not exist. We predict that microbial pesticides, such as sprayable and other Bt formulations, will continue to have a successful future in the coming decades.

3.1.5. Controversy around Bacillus thuringiensis toxins in GM crops. In this section we address the biological aspects of the controversy over the use of Bt crops and focus on safety and environmental concerns. Divisive socio-economic and political issues will not be covered and should be the subject of a separate forum discussion. The Bt toxins are essential in the deployment of a number of major insect resistant GM crops and, therefore, *B. thuringiensis* microbial pesticides were also involved in the extensive controversy around the safety and efficacy of GM crops. A notable example has been concern about effects of Bt toxins on the monarch butterfly, *Danaus plexippus*. Pollen from Bt-maize dusted onto milkweed under laboratory conditions was reported to produce mortality in *D. plexippus* larvae (Losey et al., 1999). Follow up research determined that the deleterious results were related to a specific maize variety (Bt176, no longer in commercial use) and that there was no negative impact to monarchs under field conditions (Hellmich et al., 2001; Minorsky, 2001; Pleasants et al., 2001; Sears et al., 2001; Stanley-Horn et al., 2001; Tschenn et al., 2001; Zangerl et al., 2001; Dively et al., 2004; Anderson et al., 2005). Nevertheless, the controversy generated a widespread perception that Bt-engineered crops are dangerous for the environment. This issue was revived 10 years later when France and Germany banned the Bt-maize variety MON810 on the basis of a threat to *D.*

plexippus, despite the facts that MON810 was found to be harmless to monarch larvae and *D. plexippus* is not found in Europe (Ricroch et al., 2010).

A second example relating to the health impact of Bt crops is the “StarLink case” (Bucchini and Goldman, 2002; Bernstein et al. 2003). In this instance, the StarLink product, a feed-registered insect-resistant Bt-maize engineered with the Cry9Ca toxin, was found in human food. This was followed by reports of allergic shock in consumers, although follow-up studies by the Centers for Disease Control failed to confirm any link to the Cry9Ca toxin (CDC, 2001). Nevertheless, problems were confirmed in the management and control of feed-registered BT-corn products that allowed them to be comingled with food for human consumption (Bucchini and Goldmann, 2002). The controversy subsequently led to a serious loss of market share for U.S. corn growers (Schmitz et al., 2005). An additional consequence of the controversy has resulted in stories implicating Bt crops either in health scares or as contributors to disastrous crop failures (Tirado, 2010; Coalition for GM free India, 2012). Several of these stories subsequently were shown to be untrue (Gruere et al., 2008; Brookes and Barfoot, 2013).

Bt microbial pesticides, while accepted in pest control, organic agriculture and vector control, also have become subjects of debate in the crop biotechnology arena and have been represented by some as a threat to human or environmental health. For example, Poulin et al. (2010) and Poulin (2012) demonstrated the negative trophic effect of Bti treatment for mosquito control on non-target fauna. The reduction of mosquitoes and chironomids and consequently their predators as prey of breeding house martins, *Delichon urbicum*, resulted in reduced clutch size and fledgling survival. Among other measures, Poulin et al. (2010) recommended suspension of mosquito control in certain habitats. We believe that such measures should take into account the effect of mosquito reduction on quality of life for humans and domestic animals, but most importantly the interruption of disease transmission.

A positive aspect of the debates on the safety of Bt products is that they have prompted renewed studies on actual health and environmental effects of Bt toxins. These have shown that commercially approved Bt products and Bt genes are safe and can have positive benefits for the environment, mostly through the reduced use of chemical pesticides and lack of effects on non-target organisms, (Saxena, and Stotsky, 2001; Phipps and Park, 2002; Shelton et al., 2002, 2007; Lacey and Merritt, 2003; O'Callaghan et al., 2005; Wu et al., 2005; Romeis et al., 2006; Marvier et al., 2007; Roh et al., 2007; Chen et al., 2008; Kumar et al., 2008; Wolfenbarger, et al. 2008).

3.1.6. Insect resistance and mode of action of Bt toxins. One of the most important aspects to address with Bt-based products and Bt crops is resistance management. *B. thuringiensis* shares with chemical pesticides the negative trait of producing resistance to the toxic effects in target insect populations. Resistance is the interruption of the mode of action (MOA) of any pesticide, and understanding insect resistance and proposed insect resistance strategies requires first summarizing the MOA. This section is intended to underline the sequential nature of the MOA of *B. thuringiensis* insecticidal proteins and its susceptibility to resistance. Resistance can result from the interruption of any of the step described in this section and, indeed, several mechanisms of resistance have been described. The MOA is well understood for a limited number of Bt toxins, including the Cry and Cyt families used in microbial pesticides, and the Cry and VIP in transgenic crops.

The MOA of Cry proteins is by far the best known (Whalon and Wingerd, 2003; Bravo et al., 2007, 2011; Pigott and Ellar, 2007, Vachon et al., 2012). Pathogenesis begins with the ingestion of the Bt crystal. The crystal, which contains protoxins, is then solubilized by the alkaline pH of the insect midgut and the soluble protoxins are activated by midgut serine proteases releasing the active toxin. The structure of these activated toxins has been determined for several families. In the Cry1 family, three functional domains have been identified (Li et al., 1991; Grochulski et al., 1995; Galitsky et al., 2001; Morse et al., 2001; Boomserm et al., 2005, 2006) (Figure 2). Domain I consists of 7 alpha helices organized in a barrel-like structure and is involved in pore formation. Domains II and III are comprised of layers of beta sheets that recognize specific binding sites at the surface of the midgut brush border (Pigott and Ellar, 2007). These binding sites have been identified mostly as aminopeptidase N-like proteins (APN) and cadherin-like proteins, although other putative receptors such as alkaline phosphatases (ALP), glycolipids or a 270-kda glycoconjugate (Pigott and Ellar, 2007) have been identified. Following specific binding, the toxin undergoes a change of conformation and inserts into the midgut membrane to form an ionic channel or pore (Knowles and Ellar, 1987; Vié et al., 2001; Bravo et al., 2004; Vachon et al, 2012) transporting ions with their free charged-amino acids (Masson et al., 1999; Vachon et al., 2002, 2004; Girard et al., 2009; Lebel et al., 2009). Ion transport triggers a physiological imbalance leading to the death of the cell, destruction of the midgut and ultimately death of the insect. This process of ionic imbalance, originally described as colloid-osmotic lysis (Knowles and Ellar, 1987; Bravo et al., 2004), is probably not the only mechanism involved in cell death. Signaling pathways that follow receptor binding recently have been described (Zhang et al., 2006). These pathways are triggered upon receptor activation by protein binding and initiate cell death mechanisms. However, these two mechanisms are not exclusive and could both contribute to the overall toxicity of Cry toxins as suggested by Jurat-Fuentes and Adang (2006) and discussed by Vachon et al. (2012).

Resistance to Bt toxins was first reported in *Plodia interpunctella*, an insect pest of stored grain, by McGaughey (1985; 1994). Field resistance has since been reported in diamond back moth, *Plutella xylostella*, and cabbage looper, *Trichoplusia ni*, and several major insect pests under laboratory selection (Tabashnik, 1994; Moar et al., 1995; Rahman et al., 2004, Shelton et al., 2007; Furlong et al., 2013). In common with Bt microbial pesticides, Bt crops also are susceptible to resistance problems and a number of cases have been reported, particularly with first generation single gene constructs (Rhaman et al., 2004, Shelton et al., 2007; Tabashnik, 2008; Tabashnik et al., 2008a, 2008b, 2009, 2013). Modification of the Bt binding sites is the most commonly reported resistance mechanism, however other mechanisms affecting different steps of the MOA have been described and can potentially develop (Frutos et al., 1999; Griffitts and Aroian, 2005; Heckel et al., 2007). A key point is that resistance affects both microbial pesticides and transgenic crops in the same way, and cross-resistance to other similar toxins used in both modes of delivery could occur.

3.1.7. Future directions. Since *B. thuringiensis* remains the primary sprayable microbial pesticide, the increasing demand for organic products should encourage the development of additional Bt products. Demand would also be driven partly by safety legislation requiring reduction of the number of chemical pesticides. The future sustainability of Bt crops will rely on a combination of multistacked toxin genes and refugia to delay resistance (Caprio and Summerford, 2007; Tabashnik, 2008, Head and Greenplate, 2012; Storer et al., 2012). Addressing resistance and resistance management will depend on detailed knowledge of the MOA of Bt toxins (Griffitts and Aroian, 2005; Shelton et al., 2007). Multiple-gene constructs targeting different binding sites is the basis for the gene pyramiding that underlies the development of novel generations of Bt crops (Shelton et al., 2002). In addition to discovery of more efficacious isolates and toxins, an increase in the use of Bt products and transgenes will rely on innovations in formulation, better delivery systems and ultimately, wider public acceptance of transgenic plants expressing Bt toxins.

3.2 *Lysinibacillus* (*Bacillus*) *sphaericus*

Although less commonly used than Bti for control of mosquitoes, *L. sphaericus* offers some advantages that Bti does not. Only the IIA sub-group includes isolates with larvicidal activity for mosquitoes (Charles et al., 1996). The moiety responsible for mosquito larvicidal activity in serovar 5a5b isolates of *L. sphaericus* is a binary toxin (Charles et al., 1996) with both proteins required for full toxicity. The individual roles of the toxin components were elucidated by Charles et al. (1997) and Schwartz et al. (2001). As with Bti, ingested toxins are solubilized in the alkaline midgut and cleaved to the active moiety by proteases. The two component proteins of the toxin, BinA (42 kDa) and BinB (51 kDa) bind to specific receptors on the brush border of epithelial cells of the gastric caecum and midgut and cause pore formation resulting in disruption of osmotic balance, lysis of the cells, and ultimately death of the insect (Charles et al., 1996). *L. sphaericus* binary toxin is more specific and narrower in range than the Bti toxins; it is principally active against *Culex* mosquitoes. Several *Aedes* species in the *Stegomyia* group (such as *Aedes aegypti*) are not susceptible to *L. sphaericus* formulations.

Protocols for the short-term evaluation of *L. sphaericus* formulations in the field are similar to that of Bti (Skovmand et al. 2007). Biotic and abiotic factors that influence the larvicidal activity of Bti and *L. sphaericus* include the species of mosquito and their respective feeding strategies, rate of ingestion, age and density of larvae, habitat factors (temperature, solar radiation, depth of water, turbidity, tannin and organic content, presence of vegetation, etc.), formulation factors (type of formulation, toxin content, how effectively the material reaches the target, and settling rate), storage conditions, production factors, and means of application and frequency of treatments (Lacey, 2007). *L. sphaericus* formulations have been utilized predominantly in organically enriched habitats, but they are also active against numerous species, and across several genera in habitats with low organic enrichment. The bacterium has been shown to persist longer than Bti in polluted habitats and can recycle in larval cadavers (Lacey, 2007). A disadvantage of *L. sphaericus* is the development of resistance in certain populations of *Culex quinquefasciatus* and *Cx. pipiens*. Low to extremely high levels of resistance to the *L. sphaericus* binary toxin have been reported in populations of *Cx. quinquefasciatus* in India, Brazil, China, Thailand, Tunisia and France (Charles et al., 1996; Lacey, 2007). The combination of *L. sphaericus* and toxin genes from Bti increases the host range of the bacterium and could offer a means of combatting resistance (Federici et al., 2007).

3.3 Paenibacillus **species**

Paenibacillus spp. are spore-forming obligate pathogens of larval coleopterans in the family Scarabaeidae (Klein, 1992; Klein et al., 2007; Koppenhöfer et al. 2012). The disease caused by these bacteria is known as milky disease due to the milky appearance of the hemolymph in infected larvae. Spores of the bacterium must be ingested in order to invade the hemocoel and produce an infection. Natural epizootics have been observed in *P. japonica*, but variable results have been obtained after application of spore powders. In some cases, epizootics have been induced following applications (Klein, 1992), in others, little or no activity was observed (Klein 1992, Lacey et al., 1994). The spores have been known to persist for several years in the soil

(Klein, 1992). *P. popilliae* was the first microbial pesticide registered in North America (1948) for control of *P. japonica* (Klein, 1992), but large-scale commercial development has been limited due to the requirement for *in vivo* production and the narrow host range within the Scarabaeidae. A breakthrough in *in vitro* production of *P. popilliae* and development of strains effective against other important scarab species (e.g., *Cyclocephala spp., R. majalis, A. orientalis*, and *Melolontha melolontha*) would significantly improve the marketability of these bacteria.

3.4 Serratia entomophila

The endemic non-sporeforming bacterium *Serratia entomophila* (Enterobacteriaceae) was discovered and developed in New Zealand, and is used for control of the New Zealand grass grub, *Costelytra zealandia* (Jackson et al. 1992; Jackson, 2007). Cultivation of pastures for cropping and re-sowing generally kills grass grubs and eliminates pathogenic strains of bacteria, leaving new pastures vulnerable to pest attack. This provides an opportunity for augmentative biological control, where *S. entomophila* is applied to *C. zealandia* populations to promote epizootics and prevent the occurrence of pasture damage.

Strains of the *Serratia* spp. cause amber disease in *C. zealandia* (Jackson et al., 2001). The bacterium must be ingested for toxin production to be initiated and disease progression is accompanied by a cessation of feeding, clearance of the gut and a halt in the synthesis of digestive enzymes. Infected larvae take on a distinctive amber coloration prior to death (Jackson et al., 2001). *Serratia entomophila* is now commercialized as a stabilized dry granular product Bioshield™ (Jackson et al., 1992, 2001). The formulation is stable under ambient conditions for several months and is applied using a conventional seed drill, which has enhanced adoption of this microbial pesticide by the pastoral sector in New Zealand (Jackson, 2007). Recycling of the disease through grass grub larvae produces an endemic population of pathogenic bacteria preventing recurrent damaging outbreaks of the pest. The technology for stabilization of this non-spore forming bacterium could be useful in the future for other non-spore forming entomopathogenic species of bacteria.

3.5 *Chromobacterium subtsugae*

Martin et al., (2007a, 2007b) isolated *Chromobacterium subtsugae,* a new species and genus of a motile, Gram-negative bacterium, with *per os* toxicity to larval Colorado potato beetle, *Leptinotarsa decemlineata*, adults of the corn rootworms, *Diabrotica* spp., and the southern green stinkbug, *Nezara viridula*. Encouragingly, live bacteria were not needed for toxicity to *N. viridula* adults (Martin et al., 2007b). Marrone Bio Innovations (MBI) has registered a biological insecticide/miticide (Grandevo®) containing *C. subtsugae* strain PRAA4-1T and spent fermentation medium for use on edible crops, ornamental plants and turf against defoliating caterpillars and certain Coleoptera (EPA Reg. No.: 84059-17-87865). MBI also reported the formulation to have multiple effects such as reduced fecundity and oviposition, reduced feeding and activity as a stomach poison on aphids, psyllids, whiteflies, *Lygus,* mealybugs, thrips and phytophagous mites. Genes encoding toxins and VIPs of this bacterium could conceivably be candidates for incorporation into GM crops for targeting a broad pest host range.

4. Entomopathogenic Fungi

4.1 Background and overall status

Fungi are the predominant natural pathogens in arthropod populations. Observations of epizootics among insect populations are common, indicating the great potential of these microbes for regulation of pestiferous species. Entomopathogenic fungi infect their hosts through the external cuticle and are pathogenic to both soft- and hard-bodied insects, as well as a range of other arthropods including Acari (ticks, mites). Cuticular invasion also enables fungi to infect sucking insects such as aphids, whiteflies, psyllids and scales (Burges, 2007; McCoy et al., 2009; Lacey et al., 2011). Consequently, fungi have been widely evaluated as control agents for a diverse variety of noxious arthropods of agricultural (including forestry and livestock) and horticultural importance (Chandler et al., 2000; Shah and Pell, 2003; Brownbridge 2006; Abolins et al. 2007; Charnley and Collins 2007; Jaronski 2007; Maniania et al., 2007; Wraight et al., 2007a; Zimmermann 2007a, b; 2008; Alves et al., 2008; Kaufman et al. 2008; James 2009; Glare et al., 2010; Goettel et al., 2010). Recent discoveries of the effects of entomopathogenic fungi on adult mosquitoes, including the prevention of development of vectored human pathogens within fungal infected mosquitoes, has resulted in an upsurge of research on their potential for control of mosquito-borne diseases such a malaria (Blanford et al., 2005, 2009; Scholte et al., 2003, 2004. 2005; Kikankie et al., 2010). Although entomopathogenic fungi traditionally have been regarded exclusively as pathogens of arthropods, recent studies suggest that they play additional roles in nature. Many are now known to be plant endophytes, plant disease antagonists, rhizosphere colonizers, and plant growth promoters (Vega et al., 2009; Behie et al., 2012; Jaber et al., 2014).

Several hypocrealean entomopathogenic fungi are important constituents of natural- and agro-ecosystems and appear to be ubiquitous inhabitants of soils worldwide. They have been recovered from a diverse array of geographic, climatic, and agro-ecological zones (Bidochka et al., 2001, 2002; Shimazu et al., 2002; Keller et al., 2003; Shapiro-Ilan et al., 2003a; Meyling and Eilenberg 2006a, b; 2007; Jaronski 2007; Quesada-Moraga et al 2007; Zimmermann 2007a, b; 2008; Inglis et al., 2008, 2012; Reay et al., 2008, Meyling et al., 2009; Scheepmaker and Butt, 2010). Fungi such as *Beauveria bassiana s.l.* and *Metarhizium anisopliae s.l.* are commonly found in both cultivated and undisturbed soils, although their natural distribution appears to be linked to habitat (Bidochka et al., 2001; Keller et al., 2003; Meyling and Eilenberg, 2006a; Meyling et al., 2009), and soil populations are influenced by agricultural practices (Hummel et al., 2002; Jaronski, 2007; 2010; Meyling and Eilenberg, 2007).

Fungi have many desirable traits that favor their development as biological control agents. They pose minimal risk to beneficial non-target organisms such as bees, earthworms and Collembola, which are key ecosystem service-providers, and arthropod natural enemies such as parasitic wasps and predatory beetles (Goettel et al., 2001; Traugott et al., 2005; Brownbridge and Glare 2007; O'Callaghan and Brownbridge, 2008). This enhances their potential role in IPM; the preservation of natural enemies allows them to make a greater contribution to the overall regulation of pests, and maintenance of biodiversity is increasingly recognized as being critical to the long-term productivity of our farms and forests. Their newly found attributes also provide the possibility of their use in multiple roles, for instance in addition to arthropod pest control, simultaneous suppression of plant pathogens and plant parasitic nematodes (Goettel et al., 2008; Kim et al., 2009; Koike et al., 2011) or biofertilizers (Kabaluk and Ericsson, 2007; Behie et al., 2012).

Chandler et al. (2008) considered the development of anamorphic fungi, e.g., *B. bassiana*, *M. anisopliae*, to have followed an 'industrial' pathway; mass-production systems have been devised to provide large quantities of inoculum which can then be formulated and repeatedly applied as sprays, granules, etc. (Shah and Pell, 2003; Brownbridge, 2006; Charnley and Collins, 2007). Conversely, pest control strategies using entomophthoralean fungi have relied more on ‘ecological’ approaches; accompanying research has focused on understanding conditions that promote natural epizootics, e.g. manipulating environmental conditions to enhance disease incidence and spread, use of inoculative releases to establish the disease within a pest population to achieve long-term suppression, or conservation of natural epizootics (Steinkraus et al., 2002; Steinkraus, 2006, 2007; Nielsen et al., 2007; Pell, 2007; Hajek, 2009; Solter and Hajek, 2009; Pell et al., 2010).

Commercial products based on some of the pathogenic fungi – mycoinsecticides and mycoacaricides – are primarily based on *Beauveria spp*, *Metarhizium spp.*, *Isaria fumosorosea* (formerly *Paecilomyces fumosoroseus*), and *Lecanicillium* spp. (Inglis et al., 2001; Faria and Wraight, 2007; Wraight et al., 2007; Alves et al., 2008). Table 3 provides examples of fungi used for the microbial control of several insect and mite pests. Fungal products largely occupy niche markets, often within individual countries or geographically linked regions. In most cases, fungi are actively applied as microbial pesticides to regulate pest populations, and pathways towards their development and regulation have generally mirrored those of synthetic pesticides. Despite these positive developments, fungi remain an under-utilized resource for pest management. How far has the field progressed since Lacey et al.’s 2001 publication to move us closer to realizing this biological control potential? Here, we will highlight some of the recent developments that may promote opportunities to use entomopathogenic fungi and identify some of the critical factors that still need to be addressed to enable their wider utilization.

4.2 Mode of action

All fungi have the same basic mode of action. Excellent reviews of the mechanical, molecular and biochemical processes involved in insect infection are available and consequently will not be covered here in detail (*e.g., see* Hajek and St. Leger, 1994; Hajek, 1997; Inglis et al., 2001; Charnley, 2003; Charnley and Collins, 2007; Ortiz-Urquiza and Keyhani, 2013). Insect control by entomopathogenic fungi is achieved when sufficient infective propagules (generally conidia) contact a susceptible host and conditions are suitable for a lethal mycosis to develop. Fungi have been applied for soil pest control by direct incorporation of conidia, mycelial pellets, microslerotia or inert or nutrient-based granules containing fungal propagules (conidia or mycelia) (Brownbridge, 2006; Charnley and Collins, 2007; Jaronski, 2007; Ansari et al., 2008; Jaronski and Jackson, 2008), whereas foliar-feeding pests have typically been targeted by sprays of formulated conidia (Jaronski, 2010).

Fungal isolate virulence towards different arthropod hosts varies. Virulence generally decreases with repeated sub-culture on artificial media, and can often be regained through host passage (e.g. Nahar et al., 2008). Virulent isolates generally express an abundance of spore-bound proteases, efficiently produce and release exoenzymes during cuticular penetration, and generate toxins as the fungus colonizes the host (Vey et al., 2001; Freimoser et al., 2005; Shah et al., 2005; Qazi and Khachatourians, 2007; Zimmermann 2007a; 2007b; 2008; Khan et al., 2012). Selecting superior strains exhibiting these characteristics, or manipulating isolates to promote these traits, has been seen as a way of overcoming what is often considered a significant impediment to their wider use, i.e., fungi kill their hosts too slowly. Fungal virulence can also be improved through directed genetic manipulation whereby specific genes are inserted into the fungal genome to promote expression of toxins that increase the virulence of the parent organisms, e.g., insertion of scorpion toxin genes into *M. anisopliae* and *B. bassiana* (Wang and

St. Leger, 2007; Pava-Ripoll et al., 2008; St Leger et al, 2011). In both cases, the recombinant strains exhibited dramatically increased virulence. This approach has the potential to improve insect kill and reduce the amount of inoculum needed to regulate a pest population. In addition, protoplast fusion can be used to enhance virulence and increase host range. For instance, protoplast fusion was used with several strains and species of *Lecanicillium* to develop hybrid strains with multiple effects (toxic and parasitic) against plant parasitic nematodes, plant pathogens and aphids, with plant competency (as root colonizers and endophytes), making these strains promising for development as broad-spectrum microbial pesticides targeting plant pathogens, insects, and plant parasitic nematodes (Goettel et al., 2008; Koike et al, 2011).

Entomophthoralean fungi actively eject spores when conditions are favorable (high humidity) that can rapidly infect a susceptible insect, even when these conditions only prevail for short periods (Steinkraus, 2006). This trait gives these pathogens great epizootic potential, and in many groups of insects, they are among the most important natural mortality factors. In contrast, spores of the hypocrealean fungi *Beauveria* and *Metarhizium* spp. tend to be dispersed passively, via wind currents or rain splash, although transmission can also occur when susceptible insects contact infected individuals, or conidia can be distributed on the bodies of other arthropods (Rath, 2002; Wraight and Ramos, 2002; Meyling and Eilenberg, 2006b; Meyling et al., 2006; Roy et al., 2007; Vega et al., 2007). Both hypocrealean and entomphthoralean fungi can survive repeated intervals of low humidity, recommencing development (infection) when favorable conditions return. This can result in spectacular epizootics such as those observed in whitefly infestations on cotton when the canopy closes and creates a humid microclimate that favors host infection and spread of the disease within the population (Lacey et al., 1996). These fungi can, though, infect insects even under conditions of low ambient humidity; attachment of the small conidia at infection sites within inter-segmental folds or under elytra where humidity levels are high may account for this, and the localized microclimate that exists around an insect or at the insect-leaf interface may have a more significant impact on the infection process than ambient conditions (Inglis et al., 2001; Vidal et al., 2003; Vidal and Fargues, 2007; Jaronski, 2010).

Fungi can persist in the soil for several years with new ‘flushes’ of inoculum provided following the successful infection and colonization of a susceptible host. This leads to localized high concentrations of infective conidia and greater opportunities for insect infection to occur (Enkerli et al., 2001; Rath, 2002; Milner et al., 2003; Keller et al., 2003; Meyling and Eilenberg, 2007). Long-term survival of entomopathogenic fungi within an environment appeared to be reliant upon access to susceptible hosts, though, as they were generally considered weak saprophytes (Keller et al., 2003; Hummel et al., 2002; Roberts and St. Leger, 2004; Jaronski, 2007). However, the recent discoveries of their roles as endophytes or rhizosphere competent organisms require further investigations in this regard. For those species with relatively narrow host-spectra, lack of hosts can limit their natural occurrence and longevity (Keller et al., 2003; Meyling and Eilenberg, 2007).

4.3 The changing face of fungi

A variety of molecular tools and systems now augment more traditional fungal classification schemes, allowing examination of evolutionary (phylogenetic) relationships between isolates as well as matching anamorphs and teleomorphs (Driver et al., 2000; Rehner and Buckley, 2005; Hibbett et al., 2007; Humber, 2008; Bischoff et al, 2009; Blackwell, 2010). Furthermore, they aid in the differentiation and identification of fungi in environmental samples, enable definition of potential associations (habitat, host), and may provide valuable insights that enable strain improvements or selection of isolates with specific traits (Nielsen et al., 2001; Ranjard et al., 2001; Sung et al., 2001; Bidochka et al., 2002; Enkerli et al., 2005; Huang et al., 2005; McGuire et al., 2006; Nielsen et al., 2005; Rehner et al., 2006; Hibbett et al., 2007; Inglis et al., 2007; Sung et al., 2007; Meyling et al., 2009; Enkerli and Widmer, 2010). These techniques are changing the way we observe fungi in the environment, and potentially alter pathways towards their development as MCAs.

4.4 The importance of selecting the appropriate fungal isolate and other considerations

The literature is replete with examples of fungi that have performed well in laboratory trials and shown “great potential” (Vega et al., 2012) only to fail once they were tested in the field. This has often led to a search for ‘new and better’ isolates rather than investigating underlying factors impacting performance in the environment. Without diminishing the implicit value of looking for new organisms (in general there is no shortage of excellent candidates) more research emphasis is instead needed to address critical factors to turn ‘potential’ into viable ‘product’.

Isolates must be ecologically competent to function and persist in the environment of the target pest, and selection of candidates must not be solely based on performance in an optimized bioassay system. Bioassays need to be carried out under discriminatory conditions that attempt to replicate conditions where the pathogen will be used (Butt and Goettel, 2000). Environmental and insect behavioral factors all influence pathogen activity, so their incorporation into a testing scheme will enable robust isolates to be identified prior to downstream development activities.

Fungi and arthropods have evolved complex relationships, and some soil-dwelling arthropods show adaptive behavioral responses that prevent their coming into contact with fungal inoculum (Villani et al., 2002; Thompson and Brandenburg, 2005; Baverstock et al. 2010). There also appears to be variation in the level of response to different fungal isolates or fungal growth stages, i.e. vegetative stage vs conidia (Thompson and Brandenburg, 2005), and in some instances, insects may be attracted or repelled by fungal volatiles or metabolites which could enhance or deter activity (Villani et al., 1994; Engler and Gold, 2004; Kepler and Bruck, 2006; Meyling and Pell, 2006c; Rohlfs and Churchill, 2011). Such behavioral responses should be taken into consideration when selecting appropriate strains for insect pest management, and the type of inoculum used in a pest management program. Similarly, our ability to manipulate insect behavior through the use of a variety of compounds may provide new opportunities to enhance pathogen efficacy (Roy et al., 2007).

4.5. Ecological considerations

Entomopathogenic fungi are natural components of most terrestrial ecosystems. . Greater understanding of the fundamental ecology of these organisms in the natural environment and post-application would be of immense value in the development of more ecologically sound control approaches (Wraight and Hajek, 2009; Vega et al., 2009; Roy et al, 2010a, 2010b). The lack of field data is due, in part, to the complexity of the environment and the intricate interactions between different environmental and biological factors that can confound observations around cause and effect (Jaronski, 2007). Likewise, interactions among biotic and abiotic factors, e.g., sunlight, humidity, and microbial activity on the phylloplane, affect efficacy and persistence of fungal treatments applied against foliar pests (Jaronski, 2010). While in vitro testing can provide valuable insights into fungal responses to specific inputs, they rarely yield data that can be directly extrapolated to predict field responses. More effort needs to be invested in the evaluation of effects of agricultural practices (e.g., Klingen et al., 2002a; 2002b; Hummel et al., 2002; Townsend et al., 2003) on persistence and particularly efficacy under field conditions.

Production of good ecological data has also been impeded by a historic lack of tools to examine and quantify fungal populations. Traditionally, studies have relied on time-consuming isolation and plating techniques. Similarly, risk assessments have tended to focus on interactions with macroorganisms; monitoring of interactions with other microbes has been limited and biased by our inability to culture all soil and foliar microorganisms. However, new tools and increasingly powerful molecular methods are becoming available to examine fungal communities and may be applied to the study of entomopathogens. For example, use of nuclear ITS and EF1-alpha sequences have enabled isolates to be differentiated and phylogenetic relationships within species to be determined, enabling links to geographic and host origins to be defined (Driver et al., 2000; Bidochka et al., 2001; 2002; Rehner and Buckley, 2005; Rehner et al., 2006; Inglis et al., 2008; Meyling et al., 2009; Inglis et al,, 2012). The ability to transform fungi to express the green fluorescent protein (GFP) allows GFP-mutants to be observed in-situ, and expression of the protein may be tied to specific events during infection or growth through choice of an appropriate promoter (Lorang et al., 2001; Hu and St. Leger, 2002; Skadsen and Hohn, 2004; Wu et al., 2008). A variety of other molecular techniques such as RFLP, T-RFLP, AFLP and strain-specific microsatellite markers have been used as diagnostic tools allowing fungi to be tracked in the environment (Enkerli et al., 2001; 2004; 2005; Castrillo et al, 2003; Rehner and Buckley, 2003; Schwarzenbach et al., 2007a, 2007b; Inglis et al., 2008; Enkerli and Widmer, 2010; Inglis et al., 2012). Advances in the use of PCR techniques provide highly specific methods of monitoring fungal populations in ‘real time’ and in a quantitative manner, in soils, insects, and in plants (Ownley et al., 2004; Wang et al., 2004; Entz et al., 2005; Castillo et al., 2008; Meyling et al., 2009; Enkerli and Widmer, 2010; Inglis et al., 2012). Use of qPCR with automated ribosomal intergenic spacer analysis (ARISA) allow soil microbial communities to be profiled and responses to specific events to be monitored; these techniques are likely to be increasingly applied to the study of entomopathogens to assess the fate of biological control species and their impacts on microbial community structure (Ranjard et al., 2001; Hartmann et al., 2005; Shah et al., 2009; Torzilli et al., 2006; Martin, 2007; Enkerli, 2008; Enkerli and Widmer, 2010; Inglis et al., 2012).

All biotic factors in soils are influenced by prevailing environmental conditions, soil types, nutrient status, agricultural practices and inputs in the form of pesticides and soil amendments. Intricate interactions between abiotic and biotic factors make it extremely difficult to quantify the specific effects of each of these on the dynamics of entomopathogenic fungi in soil (e.g. Quesada-Moraga et al., 2007). However, we can identify three principle biotic components that have a major influence on fungal persistence and efficacy. These are: soil microorganisms, plants, and invertebrates.

Generally speaking, entomopathogenic fungi are considered weak saprophytes in the competitive soil environment, and introduced inoculum levels will decline in the absence of an arthropod host (Inglis et al., 2001; Roberts and St. Leger, 2004; Längle et al., 2005). Metabolites produced by other soil microbes can adversely affect germination and growth, or be directly toxic, leading to reduced infectivity or multiplication; consequently, survival and efficacy of entomopathogens is commonly superior in sterilized vs non-sterilized soils (Jaronski, 2007). Even so, in native soils conidia will infect a susceptible host when they contact the insect cuticle; *Metarhizium* and *Beauveria* will germinate, grow, and conidiate when applied to soil and amendment of soil with nutrients can overcome (apparent) fungistasis (Keller, 2000; Milner et al., 2003; Bruck, 2005; Chandler and Davidson, 2005; Brownbridge, 2006; Jaronski, 2007; Jaronski and Jackson, 2008). This suggests that fungistasis alone is not the sole reason for the low germination in soil and fungi may require additional host- or nutrient-derived cues to initiate development. Antibiosis also occurs between entomopathogenic fungi and other microorganisms, a phenomenon that has implications for protection of crop plants from pathogens (Ownley et al., 2004; 2010). Very few attempts have been made to evaluate effects of phylloplane microorganisms on persistence and infectivity of fungi applied to foliage, in spite of the fact that plant surfaces are occupied by a diverse range of microfauna (Jaronski, 2010).

Crop plant species and tillage practices affect the prevalence and persistence of fungi (Hummel et al., 2002; Klingen et al., 2002b; Jaronski, 2007). Fungal entomopathogens could be affected by plant surface chemistry and volatiles (Cory and Ericsson, 2010). Some entomopathogens, particularly *M. anisopliae*, are more commonly associated with agricultural (tilled) soils than natural habitats, although fungal prevalence and diversity is normally greater in undisturbed soils (Bidochka et al. 2001; 2002; Inglis et al., 2008; Meyling and Eilenberg, 2007; Meyling et al., 2009). Plant root exudates contain many nutrients that support the development of microbial populations in the rhizosphere; in vitro tests demonstrated that carbohydrates and nitrogen compounds stimulate germination and growth of *M. anisopliae* conidia, while organic acids may inhibit germination (Li and Holdom, 1995). Some *M. anisopliae* isolates are rhizosphere-competent, a trait that enhances persistence in the root zone (Hu and St. Leger, 2002; Bruck, 2005; St. Leger, 2008). The physiological adaptation of the fungus to function as a pathogen or saprophyte involves expression of different gene products, demonstrating that the fungus appears to have evolved various mechanisms that enhance survival in different environments (Wang et al., 2005; Wang and St. Leger, 2007; Bruck, 2010; St. Leger et al., 2011).

Endophytes may be broadly defined as microbes that live in healthy plant tissue (Hyde and Soytong, 2008). Commonly, these are bacteria and fungi that have either no effect or have a beneficial relationship with their host, including the ability to naturally confer resistance to pests and diseases (Backman and Sikora, 2008). Recently, *B. bassiana* has been recognized as an endophyte that occurs naturally in, or has been successfully introduced into a diverse range of plant species (Vega et al., 2008; Parsa et al., 2013). In several instances, colonization of plant tissues by the fungus has provided protection against insect damage or has inhibited insect development and establishment, such as the banana weevil, *Cosmoplites sordidus* (Akello et al., 2008), stem borer, *Sesamia calamistis* (Cherry et al., 2004), and the cyniprid, *Iraella luteipes* (Quesada-Moraga et al., 2009), probably as a result of *in planta* production of insecticidal metabolites by triggering host-plant defenses, or as a result of feeding deterrence/antibiosis. Some isolates have also demonstrated anti-microbial activity and can provide protection against infection by plant pathogens (Ownley et al., 2004; 2010) including most recently, the zucchini yellow mosaic virus in curcurbits (Jaber et al., 2014). As endophytes, the fungi are in a protected environment where they are not exposed to abiotic and biotic factors that can limit efficacy when fungi are applied to foliage or the soil, and may offer protection against cryptic species, e.g., stem borers, that would otherwise be difficult to control (Brownbridge, 2006; Jaronski, 2007, 2010).

Foliar topography and chemistry can affect fungal activity and persistence (Jaronski, 2010). While the specific physical traits or compounds responsible for these observed differences are often unknown, the work of several authors indicate that both factors can significantly impact insect infection due to reduced rates of conidial acquisition (Kouassi et al., 2003; Ugine et al., 2007) and the toxic effects of chemicals produced (as exudates or volatiles) at the leaf surface (Inyang et al., 1998) or consumed by the host (Olleka et al., 2009). Efficacy may be further compromised by the use of inefficient application practices and different spray parameters on crops at different stages of development, which has been clearly shown to affect insect infection rates (Ugine et al., 2007). Clearly, we need to develop a better understanding of the complex interactions between a range of factors, e.g., crop type and physiology, age, fungal strain, pest biology, method of application, etc., to devise efficient use practices.

Invertebrates have many effects on entomopathogen levels in soil. Some, such as Collembola, mites and earthworms, ingest conidia and play a role in their dispersion within and removal from soil (Broza et al., 2001; Dromph, 2003; Milner et al., 2003; Brownbridge and Glare, 2007; Shapiro-Ilan and Brown, 2013). Insect hosts are critical to the long-term survival of many species of entomopathogenic fungi. Access to and successful infection of a host is the only way in which some species can significantly multiply. Fungal prevalence over time may thus be closely correlated with the presence of susceptible insect populations (Meyling and Eilenberg, 2007), although the extent that they reproduce endophytically or epiphytically remains to be determined. Use of insecticides may contribute to the decline of fungal populations by reducing the availability of suitable hosts rather than having direct negative effects on fungal survival (Klingen and Haukeland, 2006). Unfortunately, most studies on effects of chemical pesticides on viability of entomopathogenic fungi have been carried out using in vitro techniques that bear little resemblance to the agricultural system in which the pathogen will encounter the chemical. This is an area of research that could be highly beneficial. Knowledge of positive or negative interactions could allow IPM practices to be adjusted to favor insect infection.

An avoidance response to conidia of both *M. anisopliae* and *B. bassiana* has been observed in mole crickets, which may lead to inconsistent performance of these fungi in the field (Villani et al., 2002; Thompson and Brandenburg, 2005). However, there appears to be variation in the level of response to different isolates (Thompson and Brandenburg, 2005). Insects may also be attracted to fungi. Engler and Gold (2004) showed that termites were attracted to mycelial preparations and volatile extracts of *M. anisopliae*, and *P. japonica* females preferentially oviposited in soils treated with mycelia (Villani et al., 1994). This recruitment effect was also seen with black vine weevil (BVW) *Otiorhynchus sulcatus* larvae, which responded positively to *M. anisopliae*-treated media (Kepler and Bruck, 2006). Such behavioral responses should be taken into consideration when selecting appropriate strains for insect pest management and may be useful in the development of more effective biological control strategies.

4.6 Production and formulation

Following the traditional model, mass production systems have been devised to maximize inoculum yield at the lowest possible cost for use in inundative applications (Wraight et al., 2001; Cliquet and Jackson, 2005; Jackson et al., 2010; Jaronski, 2010; Jaronski and Jackson, 2012). Research emphasis has been placed on optimization of biomass production, stability, and ease of handling for application (Charnley and Collins, 2007). The general assumption has been that control could be achieved if sufficient inoculum could be produced cheaply enough and applied at sufficiently high rates (Brownbridge et al., 2008; Jaronski, 2010). The role of the environment and its impact on fungal activity has not necessarily been a primary consideration driving the development of production and formulation techniques (Jackson et al., 2010). However, there is considerable scope to modify production media and techniques to provide more ecologically competent infective material that is better suited to use in specific environments. Greater knowledge of prevailing ecological factors in the pest's habitat will allow potential constraints to fungal survival and/or infection to be identified, and will provide leads for research to overcome these constraints. When combined with development of alternative delivery mechanisms, it is likely that more efficacious microbial control products will become available.

Efficacy against soil-inhabiting pests is influenced by many biotic and abiotic factors. Consequently environmental factors are critical to performance, and maintenance of bioactivity must be a primary consideration when developing production media (Kiewnick, 2004; Tarocco et al., 2005; Brownbridge, 2006; Jaronski, 2007, 2010). Formulation can enhance characteristics or render fungal preparations easier to apply, but their performance is ultimately reliant upon inclusion of robust biological material that is "fit for purpose" (Jackson, 1999; Brownbridge et al., 2008). The production method selected will depend upon the nature of the inoculum required, and isolates may have different growth characteristics on different production media (Shah et al., 2005; Charnley and Collins, 2007; Jaronski and Jackson, 2012). An excellent overview of ecological considerations in the production and formulation of entomopathogenic fungi was recently published by Jackson et al. (2010), and readers are referred to it for a more complete review of these factors.

Solid substrates have been widely used to produce aerial conidia of entomopathogenic and other beneficial fungi (Kiewnick, 2001; Wraight et al., 2001; Krishna, 2005; Charnley and Collins, 2007; Jaronski and Jackson, 2012). Temperature, pH, aeration and substrate components all influence conidial yield, viability, stability and virulence (Jaffee and Zasoski, 2001; Shah and Butt, 2005; Shah et al., 2005; Rangel, 2006; Jackson et al., 2010). Although these parameters are more difficult to regulate in a solid-substrate system, this remains the predominant method used for commercial products due, in part, to the flexibility of a system that lends itself to the cottage-industry production scale used in many parts of the world. Solid-state fermentation bioreactors yielding up to $3x10^{13}$ conidia per kg of substrate have been developed (Jenkins and Gryzwacz, 2000; Wraight et al., 2001; Kiewnick, 2004; Kang et al., 2005; Kiewnick and Sikora, 2006; Jaronski and Jackson, 2012).

The economies of large-scale liquid fermentation processes for microorganisms is well established and has provided the paradigm for the mass production of microbes with pharmaceutical (e.g., production of insulin) or nutraceutical (e.g., probiotics) applications. Large-scale liquid fermentation systems are successfully used for agriculturally important bacteria (e.g., *B. thuringiensis*, *S. entomophila*). In submerged culture, fungi generally produce vegetative propagules – mycelia or yeast-like blastospores; culture conditions and media composition will have a primary influence on the type and amount of inoculum produced (Jackson et al., 2003; Vega et al., 2003; Cliquet and Jackson, 2005; Charnley and Collins, 2007; Jaronski and Jackson, 2012). Production systems have been designed with high yield as a primary goal but again, the infectivity of the resulting biomass and its ecological competence and stability are key factors that must be considered during process development. Culture conditions and media can be manipulated to impart specific traits to the resulting biomass, including enhanced infectivity (potency) and stability during drying and in storage (Vega et al., 2003; Cliquet and Jackson, 2005; Liu and Chen, 2005; Leland et al., 2005a; 2005b; Jackson et al., 2006; Jaronski and Jackson, 2008; 2012). Jaronski and Jackson (2008; 2012) and Jackson et al. (2010) recently described methods to induce production of microsclerotia by *M. anisopliae* in liquid media. The aggregates were readily air-dried, stable at room temperature, and showed superior efficacy against sugarbeet root maggot in soil assays compared with conventional corn-grit granules. The material sporulated profusely in non-sterile soils and was active at low soil moisture levels (Jaronski, 2007; Jaronski and Jackson, 2008). Such production/formulation techniques overcome some of the biotic and abiotic constraints to fungal efficacy and may increase opportunities to utilize these biocontrol agents against soil pests.

Advances in formulation technologies now permit stabilization of environmentally sensitive microbes and have applications to a diverse variety of beneficial organisms. Formulations can improve the handling characteristics and safety of a microorganism (e.g., by eliminating spore dust during preparation of a spray mixture), enhance stability pre- and post-application, improve persistence, promote efficacy, and facilitate easy delivery to the target pest (Wraight et al., 2001; Brownbridge, 2006; Brownbridge et al., 2006; Jackson et al., 2006; Thompson et al., 2006; Charnley and Collins, 2007; Jaronski, 2007; 2010; Jaronski and Jackson, 2008; Jackson et al., 2010). Critical, however, is maintenance of viability, ideally even when storage conditions are sub-optimal (Jackson et al., 2010). Effective formulation is integral to the wider utility of microbial pesticides in agricultural production systems, and microbes can fail if formulated poorly. Formulations may be tailored to suit the environment in which the microbial will be used, the delivery system envisioned, and the nature of the inoculum being used. Like production systems, they must be rationally developed to ensure retention of key characteristics that are critical to microbial efficacy, in both foliar and soil environments (Jaronski, 2010). For example, an oil formulation of *M. anisopliae* var. *acridum* was developed to overcome the limitations of dry habitats for the control of locusts and grasshoppers (Lomer et al., 1999, 2001; Bateman, 2004; Moore, 2008).

4.7 Improving delivery

While mass production systems can be refined to overcome particular environmental constraints, strategies for more efficient use also need to be investigated to capture the full potential of these microbes, as well as to reduce the amount of inoculum required to achieve satisfactory control because there is a physical and economical limit to the amount of material that can be applied. Some circumstances may require repeated pesticidal application of fungal biocontrol agents where simple sprays are not appropriate or effective. Control of cryptic insects, for example, cannot be achieved using conventional sprays. We thus need to look to application techniques that are not only more efficient, but use less material. As with other development criteria, consideration of the pest's biology is paramount to devising novel delivery techniques.

The pollen beetle *Meligethes aeneus,* is a widespread pest of oilseed rape and other important cruciferous crops in Europe. Adults and larvae feed on pollen in buds and open flowers, affecting seed set and hence yield. The beetles are very difficult to reach with regular sprays in this protected environment. Honey-bees (*Apis mellifera*), frequent visitors to oilseed crop flowers to forage for nectar and pollen,,were successfully used to vector dry *M. anisopliae* conidia to flowers of oilseed rape, leading to subsequent high levels of pollen beetle mortality and mycosis (Butt et al., 1998). Honey bees have subsequently been used to disseminate *B. bassiana* to canola flowers for control of tarnished plant bug, *Lygus lineolaris* (Al-mazra'awi et al., 2006a) and can vector dry conidia to a range of agriculturally important crops, demonstrating additional opportunities to use bees to deliver these control agents (Al-mazra'awi et al., 2007). Bumble bees are used to pollinate many greenhouse crops, and can also be employed to vector *B. bassiana* and other microbial inoculants to control thrips, tarnished plant bug and grey mold in greenhouse tomato and sweet pepper (Al-mazra'awi et al., 2006b). In all cases, fungal delivery was efficiently targeted to the portion of a crop where pest damage was occurring, and relatively small amounts of conidia were needed to effect control (Kapongo et al. 2008 a, 2008 b; Kevan et al., 2008).

Fungi can be delivered into the soil environment via seed coatings. This technique has traditionally been used to protect seeds and developing seedlings from soil-borne diseases and subterranean pests with persistent broad-spectrum fungicides and insecticides. With the advent of new polymers that can be used to coat materials onto seeds without heat, seed-coating with microbes has become possible. Seed coating with fungal inoculants can be used to establish fungi such as *Trichoderma* spp. in the rhizosphere and prevent losses to root diseases. Rhizo-competent entomopathogens such as *M. anisopliae* may establish on the developing roots of seedlings, mitigating insect damage, and endophytic entomopathogens such as *B. bassiana* may colonize the plant providing resistance to plant pathogens. Although the biological control effectiveness of these approaches needs to be validated, targeted suppression of a pest with reduced amounts of inoculum could be provided.

Efficiencies may also be realized using auto-dissemination devices. Several insect pests have been effectively regulated using this approach (Vega et al., 2007; Baverstock et al., 2010). Tsetse flies, *Glossina* spp., are major impediments to rural development in many African countries. Previous control attempts have focused on habitat manipulation and widespread application of insecticides. The long-term efficacy of these approaches is poor and the high cost and environmental risks posed by widespread insecticide applications have provided the impetus to develop alternative management approaches. Area-wide spray applications of fungi are impractical due to issues of cost, targeting, and poor field persistence, creating an ideal scenario for development of an auto-inoculation device. Various traps have been devised that are highly attractive to tsetse, e.g., bi-conical traps baited with cow urine (Dransfield et al., 1990); by combining this technology with an inexpensive trap-and-release inoculation device, an efficient and economical method of delivering lethal doses of *M. anisopliae* conidia to adult tsetse was developed in Kenya (Maniania et al., 2002). A similar approach was taken to the development of an auto-dissemination device for control of adult fruit flies (Dimbi et al., 2003; Ekesi et al., 2007). The potential for horizontal transmission among inoculated individuals further enhances the likelihood that these pests can be controlled using fungi in an auto-inoculation device (Quesada-Moraga et al., 2008; Thaochan and Ngampongsai, 2015).

Auto-dissemination devices show promise for use against pests of field vegetable and fruit crops, and in forested areas, where widespread conventional applications of fungal pathogens are impractical. A common behavioral phenomenon among many beetles is that they overwinter *en-masse*, providing opportunities to target a fungal treatment to a compact population (Dowd and Vega, 2003). Overwintering sap beetles, *Carpophilus luqubris,* were contaminated and infected with a virulent strain of *B. bassiana* using an auto-inoculative device baited with pheromones. Insects were targeted as they left harvested cornfields in the fall; the disease spread within the population by horizontal transmission and established in the overwintering population (Dowd and Vega, 2003). Autoinoculative devices were also successfully used to introduce *B. bassiana* into a population of spruce bark beetle, *Ips typographus* (Kreutz et al., 2004). Transmission of the pathogen occurred between treated and non-treated individuals and significantly reduced adult beetle damage to spruce trees and numbers of beetle larvae under spruce bark. The capacity to control other insects of agricultural importance using this technology has been reviewed by Vega et al. (2007). This includes pests with cryptic habits such as leafminers, which are very difficult to control with microbial or conventional pesticides (Migiro et al., 2010). Knowledge of pest biology is essential to the development of these novel yet simple technologies, which have excellent potential to provide selective and cost-efficient means of control.

Insect behavior may be manipulated with a variety of allelochemicals and other compounds in ways that may improve the efficiency of pathogen-based pest control strategies (Pell et al., 2007; Baverstock et al., 2010). For example, a variety of thrips allelochemicals will attract, arrest or repel these insects, raising the possibility of using these materials to concentrate thrips into specific areas of a crop (Tsao et al., 2005; Teulon et al., 2007a, 2007b; Davidson et al., 2007; 2008). Use of attractants with repellent compounds allows us to consider development of a "push-pull" approach in greenhouse crops (van Tol et al., 2007). By concentrating infestations in a limited area, control efforts can be focused there, rather than blanket-spraying an entire crop.

The differential attraction of some insect pests to particular plant varieties or species offers another way in which pest behavior can be modified to enhance the efficacy of fungal biocontrol agents. For example, western flower thrips are more strongly attracted to some varieties of chrysanthemum, which can be used as 'trap plants' within a production system (Buitenhuis and Shipp, 2006). Trap plants can be arranged as "islands" within a crop and fungal biocontrol agents applied to the islands within a wider cropping area. Despite a wide host range, the black vine weevil has distinct preferences for feeding and oviposition. Adults are differentially attracted to plant volatiles (van Tol et al., 2002), and insect feeding damage on *Taxus* and *Euonymous* spp. invokes the production of odors that are highly attractive to other beetles (van Tol et al., 2002; 2004). These and other attractive plants can be used as trap crops to limit weevil distribution and egg-laying to specific areas, allowing control efforts such as *M. anisopliae* (Bruck, 2005; Shah et al., 2007) to be focused on the trap plants. Furthermore, some fungi appear to attract the weevils, which may further improve efficacy (Kepler and Bruck, 2006). By defining more efficient use practices for insect pathogens, such controls become more cost-effective.

Synergistic interactions have often been observed when fungal pathogens have been co-applied with sub-lethal doses of insecticides. Synergism is thought to occur due to the action of the insecticide on the insect's behavior, either stimulating movement through treated media in an attempt to escape to a less toxic environment and, in the process, leading to the acquisition of more fungal inoculum, or adversely affecting movement and grooming behavior, leading to greater retention of inoculum on the body of an insect (Quintela and McCoy, 1998; Jaramillo et al., 2005; Shah et al., 2007; 2008; Ansari et al., 2007). Synergism leading to improved efficacy and control may also occur when different species or strains of fungi are applied concurrently. For example, combined application of *B. bassiana* and *M. acridum* (identified as *M. flavoviride)* could be used to overcome some of the constraints of temperature in thermoregulating pests such as grasshoppers, especially where temperatures fluctuate or are high for a significant period of time (Inglis et al., 1997). Application of entomopathogenic fungi can also be practiced in combination with other insect pathogens, including nematodes and Bt (Ansari et al., 2008; 2010; Wraight et al., 2009). Combined applications may render the insect host more susceptible by way of compromising health, prolonging developmental stages, or simply by the combined action of two microbes on different components of the pest population. Similar effects can be obtained by using entomopathogens in combination with predators or parasitoids (Roy and Pell, 2000; Wraight, 2003. For example, Labbé et al. (2009) demonstrated that applications of *B. bassiana* for control of greenhouse whiteflies (*Trialeurodes vaporariorum*) was compatible with concurrent use of the parasitoid, *Encarsia formosa*, and the generalist predator, *Dicyphus hesperus*.

Clearly, opportunities exist to use a variety of mechanisms to improve the efficiency of fungal biocontrol strategies. Such approaches can reduce the amount of inoculum needed to control a pest and provide protection against environmental factors that would otherwise rapidly degrade the organism post application, while improving efficacy and cost-effectiveness. This area needs to be explored further rather than remaining focused on the pesticide paradigm.

4.8 Conservation biological control

Contrary to the inoculative or augmentative approaches discussed above, conservation biocontrol relies on the modification of habitats or of crop management techniques to promote the impact of ecosystem service providers, specifically the natural activity of biocontrol agents within a crop system (Steinkraus, 2007; Pell et al., 2010). The successful use of this approach relies on a thorough understanding of the biology and ecology of the pest and the natural enemy complex and, in the case of fungi, conditions that promote the development of epizootics (Pell et al., 2010; Meyling and Hajek, 2010). Although conservation biocontrol may be considered to be in its infancy for entomopathogens, this tactic has been successfully used on a large scale. For example, predictive systems have been devised to inform farmers when conditions favor the development of natural epizootics of *Neozyygites fresenii* in cotton aphids, reducing the need for other mitigation strategies (Steinkraus et al., 2002; Steinkraus, 2007). There are opportunities to create a new norm around the ‘use’ of these natural enemies. They do not necessarily create commercial opportunities for sale of bioinsecticides, however development of systems whereby environmental conditions can be manipulated to promote the natural incidence and efficacy of fungi can provide an environmentally friendly and efficacious method for pest management. Both entomphthoralean and hypocrealean entomopathogenic fungi can make a significant contribution to pest reduction and can form the foundation of an integrated crop management program (Meyling and Eilenberg, 2007; Pell, 2007; Pell et al., 2010).

Greater adoption of fungal controls in agriculture will rely on achieving greater efficacy, cost reduction, and an ability to broaden the range of pest species that may be targeted. Many of these potential approaches go beyond the use of fungi as microbial pesticides, and require a more ecological approach to their application.

There are several key areas where we must continue to derive new knowledge to advance the development and use of fungal controls. Detailed knowledge of fungal ecology is needed to better understand their role in nature and limitations in biological control. More efficient mass production, formulation, and delivery systems are needed to supply a larger market; most fungi are mass-produced using solid substrates and there are obvious physical limitations to the amount of inoculum that can be produced using these processes. More testing under field conditions is required to identify effects of biotic and abiotic factors and their interactions on efficacy, persistence, and potential limitations to the use of these biocontrol agents in certain crops or locations; and greater investment in the optimization of use practices is needed. There are great opportunities to use fungi in classical and conservation biological control approaches that can improve environmental stability, efficacy and the cost effectiveness.

5. Entomopathogenic Nematodes

5.1 Background and overall status

Although there are numerous nematode taxa that have shown potential in biological control, the entomopathogenic nematodes (EPN), Rhabditida: Steinernematidae and Heterorhabditidae, have been most successful and have received the most attention (Grewal et al., 2005a), and therefore constitute the focus in this article. We include only a brief description of EPN basic biology and life cycles; more detailed aspects may be found elsewhere (e.g., Kaya and Gaugler, 1993; Gaugler, 2002; Grewal et al., 2005).

EPNs kill arthropod hosts via a mutualistic symbiosis with bacteria, *Xenorhabdus* spp. and *Photorhabdus* spp. for steinernematids and heterorhabditids, respectively (Poinar, 1990). Infective juveniles (IJs), the only free-living stage, enter hosts through natural openings (mouth, anus, and spiracles), or in some cases, through the cuticle. After entering the host's hemocoel, nematodes release their bacterial symbionts, which are primarily responsible for killing the host within 24-48 hours, defending against secondary invaders, and providing the nematodes with nutrition (Dowds and Peters, 2002). The nematodes molt and complete up to three generations within the host, after which IJs exit the cadaver to find new hosts (Kaya and Gaugler, 1993). EPNs possess many positive attributes as biological control agents (Shapiro and Grewal, 2008). They are safe to humans and are generally safe to other nontarget organisms and the environment (Akhurst and Smith, 2002; Ehlers, 2005), which has led to a lack of pesticide registration requirements in many countries such as the United States and nations in the European Union (Ehlers, 2005). With few exceptions, e.g., *Steinernema scarabaei* (Koppenhöfer and Fuzy, 2003), entomopathogenic nematodes have a wide host range. Some nematode species have been reported to infect dozens of insect species across five or more orders (Poinar, 1979; Klein, 1990), and certain nematode species are used commercially against 12 or more insect species (see Table 4). Entomopathogenic nematodes are amenable to mass production using *in vivo* (infected insects) or *in vitro* (solid or liquid fermentation) methods (Shapiro-Ilan and Gaugler, 2002; Shapiro-Ilan et al., 2014a).

A number of biotic and abiotic factors affect EPN pest control efficacy (Kaya and Gaugler, 1993; Shapiro-Ilan et al., 2002a; Shapiro-Ilan et al., 2006a). Biotic factors such as choice of nematode species and rate of application (generally a minimum of 25 IJs per cm^2 is required) are critical (Shapiro-Ilan et al., 2002a). Environmental factors are also critical in determining efficacy of EPN applications (Shapiro-Ilan et al., 2006a; Shapiro-Ilan et al., 2012b). For example, the nematodes are highly sensitive to desiccation and ultraviolet light, thus applications made to soil or other cryptic habitats, and made during the early morning or evening, tend to be most successful. EPNs have been developed as biocontrol agents on a commercial level. They are currently being produced by at least 12 companies in Asia, Europe, and North America (Kaya et al., 2006), and, to date, at least 13 different species have reached commercial development, application, and sales: *Heterorhabditis bacteriophora*, *H. indica*, *H. marelata*, *H. megidis*, *H. zealandica*, *Steinernema carpocapsae*, *S. feltiae*, *S. glaseri*, *S. kushidai*, *S. kraussei*, *S. longicaudum*, *S. riobrave*, and *S. scapterisci* (Lacey et al., 2001; Georgis et al., 2006; Kaya et al., 2006: Shapiro-Ilan et al., 2014a). Commercial application extends to a considerable variety of economically important pests in various commodities (Table 4) (Shapiro-Ilan and Gaugler, 2002; Georgis et al., 2006). Significant advances have increased the biocontrol utility of EPNs since 2001; new pests have been targeted, production and application technologies have been improved, and our fundamental knowledge of ecology and genetics has greatly expanded. The following is an update in research progress relative to EPN application since 2001.

5.2 Novel EPN targets

The quest to develop EPNs for new target pests has remained active. High levels of efficacy have been demonstrated against previously untested (or insufficiently tested) insect pests. Most of the new targets are soil pests because the environment is favorable for EPNs. For example, EPNs have caused substantial field suppression (75 to 100%) in two root-boring pests of stone fruits, the Mediterranean flat-headed rootborer, *Capnodis tenebrionis* (L.) (Morton and Garcia-del-Pino, 2008; Martinez de Altube et al., 2008) and the peachtree borer, *Synanthedon exitiosa* (Cottrell and Shapiro-Ilan, 2006; Shapiro-Ilan et al., 2009a). In addition to root-borers, advances have been made in effectively controlling soil-dwelling stages of other insect pests, such as the filbertworm, *Cydia latiferreana* (Bruck and Walton, 2007; Chambers et al., 2010), guava weevil, *Conotrachelus psidii* (Dolinski et al., 2006), large pine weevil, *Hylobius abietis* L. (Dillon et al., 2007; Williams et al., 2013b), navel orangeworm, *Amyelois transitella* (Siegel et al., 2006), pecan weevil, *Curculio caryae* (Shapiro-Ilan et al., 2006b), plum curculio, *Conotrachelus nenuphar* (Shapiro-Ilan et al. 2004a, 2008a, 2013; Alston et al., 2005; Pereault et al., 2009), oriental fruit moth, *Grapholita molesta*, (Riga et al., 2006; De Carvalho et al., 2013), and small hive beetle, *Aethina tumida* (Ellis et al., 2010; Shapiro-Ilan et al., 2010a).

New developments in EPN usage have also taken place in non-soil habitats. Because nematodes are sensitive to adverse environmental conditions, a major barrier to expanded use of EPNs has been difficulties encountered with application to aboveground targets. Nevertheless, some significant progress has been made in that arena over the past several years, including the application of *S. feltiae* for control of the sweetpotato whitefly, *Bemisia tabaci,* in the greenhouses (>80% control) (Cuthbertson, et al., 2007) and application of *S. carpocapsae* for control of *P. xylostella*, which is enhanced by a novel surfactant-polymer formulation (Schroer and Ehlers, 2005; Schroer et al., 2005). Furthermore, *S. carpocapsae* treatments for control of the lesser peachtree borer, *Synanthedon pictipes,* were greatly enhanced by a follow-up application of a sprayable gel that is commonly used for protecting structures from fire (Shapiro-Ilan et al., 2010b), and *S. carpocapsae* treatments resulted in high levels of suppression of the red palm weevil, *Rhynchophorus ferrugineus* when applied in a chitosan formulation (Llàcer et al., 2009).

Applications of EPNs to apple tree trunks for control of codling moth, *C. pomonella*, were improved when the treatments included the sprayable fire-gel or wood flour foam as a protective agent (Lacey et al., 2010). Additionally, some promise has been demonstrated for using EPNs for control of stored product pests (Mbata and Shapiro-Ilan, 2005; Ramos-Rodriguez et al., 2006; Athanassiou et al., 2008).

In addition to developing new targets for EPNs, significant expansion and improvements have been made in the control of a number of "traditional" target pests, i.e., those that have been considered commercial targets, or potential commercial targets, for over a decade. A case in point is the use of EPNs for control of white grubs (Coleoptera: Scarabaeidae). Advances in white grub control have been made based on the discovery of new highly virulent steinernematid and heterorhabditid species or strains, as well as an in-depth analysis of nematode-host specificity and elucidation of the mechanisms behind that specificity (e.g., differences in infection routes and optimum soil parameters) (Koppenhöfer and Fuzy, 2003; 2007; An and Grewal, 2007; Grewal et al., 2004; Koppenhöfer et al., 2006; 2007).

A new discovery of particular promise is the recently discovered *S. scarabaei*, which is highly virulent against a variety of white grubs and exhibits long-term persistence in the soil environment (Stock and Koppenhöfer, 2003; Koppenhöfer and Fuzy, 2003; Koppenhöfer et al., 2009). Additionally, enhanced control of codling moth, *C. pomonella* was observed based on use of optimum application equipment, addition of adjuvants, and mulching (Unruh and Lacey, 2001; Lacey et al., 2006a,b). A novel control approach for codling moth is to add EPNs to the water in apple dump tanks, thereby targeting the overwintering insects that are harbored in infested fruit bins (Lacey et al., 2005; de Waal et al., 2010). Advances in suppression have been made for other established target pests including fungus gnats (Diptera: Sciaridae) (optimized substrate media and timing of applications) (Cloyd and Zaborski, 2004; Jagdale et al., 2004; 2007), the diaprepes root weevil, *Diaprepes abbreviatus* (expansion of control to other host plants) (Jenkins et al., 2008), grape root borer, *Vitacea polistiformis*, (Williams et al., 2010), and the western corn rootworm, *Diabrotica virgifera virgifera*, in Europe (Toepfer et al., 2008).

Research has progressed significantly beyond direct application of EPNs as single control agents for suppression of insect pests. Studies on combining EPNs with other control tactics have increased substantially since 2001. Positive/synergistic interactions have been observed among various novel combinations with chemicals (Koppenhöfer et al., 2002; Polavarapu et al., 2007; Koppenhöfer and Fuzy, 2008; Reis-Menini et al., 2008), microbial agents (e.g., *M. anisopliae s.l.*) (Ansari et al., 2004; 2006a; Acevedo et al., 2007) and arthropod predators (Premachandra et al., 2003). However, neutral or negative interactions with these agents may also be observed depending on the specific pathogens, hosts, or application parameters (Koppenhöfer et al., 2002; Shapiro-Ilan et al.2004b). Interestingly, entomopathogenic nematodes have also been reported as synergists in conjunction with GM crops (i.e., Bt-corn) (Gassmann et al., 2008).

EPN research has expanded beyond the targeting of insects pests to include such pests as plant-parasitic nematodes; efficacy in control of plant parasitic nematodes using EPNs has varied based on a number of factors such as target species and the cropping system (Lewis et al., 2001; Fallon et al., 2002; 2004; Jagdale et al., 2002, 2009; Nyczepir et al., 2004; Perez and Lewis 2004; Lewis and Grewal, 2005; Shapiro-Ilan et al., 2006c). Finally, research has included utilization of nematode symbiotic bacteria partners (separate from the nematodes) or byproducts thereof, as control mechanisms for arthropods (Mohan et al., 2003; Jung and Kim, 2006; Bussaman et al., 2006; ffrench-Constant et al., 2007; Abdel-Razek, 2010; Da Silva et al., 2013) or plant pathogens (Isaacson and Webster, 2002; Ji et al., 2004; Böszörmènyi et al., 2009; Shapiro-Ilan et al., 2009b).

5.3 Advances in basic research

Fundamental research on EPNs expands utility of the organisms in biological control efforts. Basic research in ecology of EPNs has progressed substantially in the past several years. For example, a number of advances in understanding the dynamics of host attraction and infection have been made. Novel cues eliciting EPN responses have been discovered including vibration (Torr et al., 2004), electromagnetic stimuli (Shapiro-Ilan et al., 2009c, 2012a; Ilan et al., 2013), and attraction to plant roots in response to chemical “distress calls” triggered by pest attack (van Tol et al., 2001; Rasmann et al., 2005; Ali et al., 2013). Plant roots were also found to enhance nematode infection by providing routes for nematode movement (Ennis et al., 2010). Infection and foraging behaviors such as jumping response (Campbell and Kaya, 1999; 2002), response to host exudates (Kunkel et al., 2006), differential response to infected vs. uninfected hosts (Christen et al., 2007; Ramos-Rodriguez et al., 2007), chemical signaling (Kaplan et al., 2012) and olfactory response (Dillman et al., 2012), and competition within the host (male fighting) (Zenner et al., 2014) have been elucidated. Additionally, broad models of host-parasite infection dynamics have been developed and/or tested, such as the phased infectivity hypothesis (Campbell et al., 1999; Dempsey and Griffin, 2002; Ryder and Griffin 2003), optimal infection strategies based on trade-offs (Fenton and Rands, 2004), risk-sensitive infection and “follow the leader” behavior (Fushing et al., 2009), and aggregative group movement/foraging behavior (Shapiro-Ilan et al., 2014b). These discoveries greatly expand our knowledge of factors that drive foraging and infection strategies (e.g., the discovery of aggregative movement suggests that nematodes may move together in the soil in groups, akin to a pack of wolves).

Fundamental research has also progressed in the realm of soil ecology. Insight has been gained into interactions with other biotic agents such as phoretic associations (Campos-Herrera et al., 2006), an alternative role for EPNs as scavengers rather than parasites (San-Blas and Gowen, 2008), food web response and competition among entomopathogenic or non-entomopathogenic nematode species (Millar and Barbercheck, 2001; Somasekhar et al., 2002; Duncan et al., 2003a, 2003b, 2007; Hodson et al., 2012), and deterrence or susceptibility to antagonists (Zhou et al., 2002; El-Borai et al., 2009). Some of these relationships, e.g., phoretic associations causing enhanced EPN dispersal, have direct impacts toward improved biocontrol efficacy (Shapiro-Ilan and Brown, 2013). Additionally, advances were made in elucidating the impact of soil habitat complexity in reference to EPN spatial dynamics and trophic cascade theory (Efron et al., 2001; Spiridonov et al., 2007; Denno et al., 2008; Hoy et al., 2008; Jabbour and Barbercheck, 2008; Ram et al., 2008). Research focused on soil dynamics, such as the studies cited above, elucidate biotic and abiotic factors that impact nematode distribution and persistence and therefore directly impacts our ability to enhance efficacy of short-term inundative applications, and also serves as foundation for development of inoculative, classical, or conservation approaches (Loya and Hower, 2002; Preisser et al., 2005; Adjei et al., 2006; Barbara and Buss, 2006; Stuart et al., 2008).

Expansion of basic research in entomopathogenic nematology has also been made through extensive progress in fundamental genetic studies including molecular genetics and genomics. Of particular note, the entire genomes of entomopathogenic nematodes and their symbionts have been sequenced (e.g., Duchaud et al., 2003; Bai and Grewal, 2007; Ciche, 2007; Bai et al., 2009, 2013; Schwartz et al., 2011; Bai et al., 2013). Additional tools (i.e., RNAi) for evaluating functional genomics of the sequence as it becomes available have been developed (Ciche and Sternberg, 2007), and analyses of certain EPN genes and their expression have already been reported including genes related to stress, involvement in host colonization, and the host-pathogen relationship (Chen et al., 2006; Sandhu et al., 2006; Bai and Grewal, 2007; Tyson et al., 2007; Cowles and Goodrich-Blair, 2008; Hao et al., 2008; Somvanshi et al., 2008; Bai et al., 2009; Easom et al., 2010; Hao et al., 2012). Given the unique characters of EPN biology and the progress made in genetic studies, the entomopathogenic nematode-bacterium complex is being developed and recognized as model system for understanding pathogenicity and symbiosis (Goodrich-Blair, 2007; Clarke, 2008; Hussa and Goodrich-Blair, 2013).

Although the outcomes may not be immediately apparent, advancements in molecular genetics and genomics will cultivate the development of new tools for enhancing biocontrol with EPNs. Additionally, significant progress has been made in applied genetic studies that may have more near-term benefits to EPN utility. For example, new EPN strains with enhanced traits (e.g., environmental tolerance) have been developed through genetic improvement methods of selection and or hybridization (Strauch et al., 2004; Ehlers et al., 2005; Shapiro-Ilan et al., 2005; Nimkingrat et al., 2013). Beneficial trait deterioration is a significant problem that can occur during repeated EPN culturing; for example, virulence, environmental tolerance and reproductive capacity can decline after several passages *in vivo* (Bai et al., 2005; Bilgrami et al., 2006). Insights into the nature of beneficial trait deterioration (Bai et al., 2005; Bilgrami et al., 2006; Wang et al., 2007) as well as the discovery of methodologies to overcome the problem, e.g., through the creation of homozygous inbred lines (Bai et al., 2005; Anbesse et al., 2013), and insight into the specific genes that change (Adhikari et al., 2009) will foster maintenance of strain stability and biocontrol performance.

5.4 Production and application technology

Considerable advances in EPN production and application technology have been made, including liquid culture media improvement (Gil et al., 2002; Islas-López et al., 2005; Chavarría-Hernández et al., 2006) and increased understanding of the EPN biology, population dynamics, and physical parameters within the bioreactor (Chavarría-Hernández and de la Torre, 2001; Han and Ehlers, 2001; Neves et al., 2001; Johnigk et al., 2004; Chavarría-Hernández et al., 2008; Hirao and Ehlers, 2010; Hirao et al., 2010; Belur et al., 2013). Detailed microbiological and molecular aspects of the EPN life-cycle have also been elucidated (Chaston et al., 2013; Moshavov et al., 2013). In vivo production of EPNs has been enhanced through the development of mechanized equipment (Gaugler et al., 2002) and improved inoculation procedures (Shapiro-Ilan et al., 2002b; Brown et al., 2006; Shapiro-Ilan et al., 2008b).

Aqueous application has benefited from advanced understanding the impacts of various types of application equipment on the EPNs (Fife et al., 2003; 2004; 2006; Brusselman et al., 2012). Additionally, in terms of application technology, substantial interest in the approach of using infected host cadavers as a vehicle for EPN distribution has been garnered. In this approach, nematode infected hosts are applied to the target area and pest suppression is achieved by the progeny IJs that emerge from the insect cadavers. Over the past several years, a number of different pests have been targeted using the infected host application method (Bruck et al., 2005; Dillon et al. 2007; Del Valle et al., 2008; Jagdale and Grewal, 2008). Research has confirmed that, relative to application in aqueous suspension, infected host application can be superior in

EPN infectivity, survival, dispersal, and pest control efficacy (Perez et al., 2003; Shapiro-Ilan et al., 2003b; Fujimoto et al., 2007). Moreover, studies indicate that the approach can be facilitated by formulating the infected hosts in coatings (Shapiro-Ilan et al., 2001; 2010a; Ansari et al., 2009; Del Valle et al., 2009) using hard-bodied insects as the host (Shapiro-Ilan et al., 2008c) and development of equipment to distribute the cadavers (Zhu et al., 2011). Nonetheless, the cadaver application method has thus far only been used commercially on a very small scale relative to conventional methods.

5.6 The future for entomopathogenic nematodes

EPNs have been cultured commercially for more than 25 years. Substantial progress has been made in terms of the number of insect pests that are targeted as well as the number of different nematode species produced. Nonetheless, commercial level application has not reached expectations. In the 1980s and 1990s, companies projected sales of well over $100 million, yet currently the market is closer to only 10% of those projections (Gaugler and Han, 2002; Georgis, 2002). A number of barriers exist that have hindered further expansion of EPN markets including cost of product, efficacy, and shelf life. These barriers may be overcome through a variety of endeavors as outlined below.

One approach to improving efficacy and expanding the list of target pests to which EPNs can be marketed is to improve the EPNs themselves. Methods to improve and expand the use of EPNs include discovery of more effective strains or species and genetic improvement via selection, hybridization or molecular manipulation (Gaugler, 1987; Burnell, 2002; Grewal et al., 2005b). Discovery of new strains and species is a straightforward approach that can quickly lead to enhanced efficacy based on innate differences in nematode virulence, environmental tolerance, or other properties. For example, in the 1990s, the discovery and subsequent commercialization of *S. scapterisci* for control of mole crickets and *S. riobrave* for *Diaprepes* root weevils and other insects made a considerable impact on EPN markets (Shapiro-Ilan et al., 2002a). The rate of EPN species discovery has been increasing dramatically (Poinar, 1990; Adams and Nguyen, 2002; Stock and Hunt, 2005). Of the more than 90 EPN species reported to-date (e.g., in the last nine decades) more than 40% have been described in the last decade (after 2001). Additionally, the numerous new strains of existing species that are being discovered can also offer enhanced virulence or other properties (e.g., Stuart et al., 2004). Certainly the number of new strains and species will continue to rise, adding more potential options for biocontrol development. However, in order to leverage the advantages that strain/species discoveries offer, biocontrol characterization of these new organisms must keep pace with the survey/discovery research. Currently, less than 20% of the >35 species discovered since 2001 have been tested for biocontrol efficacy in the laboratory, greenhouse, or field; clearly there is significant untapped potential. In addition to expanded utility derived from discovery, we can also expect the upcoming advances in genomics (Bai and Grewal, 2007; Ciche, 2007; Bai et al., 2009, 2013) to offer substantial opportunities for directed strain improvement through genetic methods.

Improved production, formulation and application technology will lead to improved efficacy. Production efficiency and reduced costs are expected with the recent significant increase in number of laboratories or companies that are researching liquid culture methodology as well as the renewed interest in developing efficient automated in vivo systems (de la Torre, 2003; Ehlers and Shapiro-Ilan, 2005; Shapiro-Ilan et al., 2014a). Additionally, fruitful advancements are expected through implementation of novel approaches to application such as distribution of infected hosts, attract and kill methodologies, slow-release teabags, habitat manipulation, and prophylactic plant dips as well as advanced research on the impact of application equipment (Wright et al., 2005a; Hiltpold et al., 2012; Nielsen and Lewis, 2012; Duncan et al., 2013). In contrast to production technology, with a few exceptions, activity in development of improved formulation has lagged, and shelf life (particularly at room temperature) continues to be a barrier to expansion of EPN markets. Thus, creative solutions to developing superior formulations are needed; alternatively, new approaches to marketing e.g., "fresh" marketing, where shelf life is not a substantial issue, may be an option.

Commercial use will also expand as the list of target pests deemed suitable for application increases. As indicated above, research toward increasing the use of EPNs to control new or existing targets has been an active area of research over the past decade and we can expect that such efforts will continue. Expansion of target pests and markets depends largely on establishment of field efficacy. At a certain point, if innate virulence is too low then there is little chance for success (Shapiro-Ilan et al., 2002a). Thus, substantial research efforts have been devoted to determining field efficacy, and a large body of literature has demonstrated high levels (e.g., ≥ 75%) of control against numerous economically important pests (Klein, 1990; Shapiro-Ilan et al., 2002a; Grewal et al., 2005a) (Table 4). Note that some pests listed in Table 4 have never become significant commercial targets despite the fact that high levels of efficacy can be demonstrated under field conditions. Thus it is clear that efficacy is not the sole factor for establishing market success.

It also should be noted that some of the commercial targets pests are not necessarily strongly supported by high levels of field efficacy (e.g., ≥ 75%) reported in several refereed papers. Possibly, some of these pests are not actually suitable for control with EPNs, but are listed as targets by some commercial companies nonetheless. In some of these cases however, it may be that substantial "in-house" research by EPN producers led to the existing markets. Alternatively, it may be that for some target pests, high levels of efficacy, similar to that expected for chemical pesticides, may not be necessary for EPN success.

6. Commercialization

Although research into the use of entomopathogens as MCAs has been conducted for over 150 years (Davidson, 2012) much of the effort has failed to lead to commercially successful microbial pesticide products. While some of the issues are related to biological constraints, a major factor is the absence of a clearly understood model for the commercialization of MCAs. A variety of factors contribute to the potential for market success, which is essentially a measure of cost and benefits including expected protection of the crop and crop value, and efficiency of competing products (Black et al., 1997; Shapiro-Ilan et al., 2002a; 2012b; Ravensberg, 2011; Glare et al., 2012). The development of MCAs is an extremely complex business, which many scientists fail to appreciate properly (Lisansky, 1997).

The publication of the book *A Roadmap to the Successful Development and Commercialization of Microbial Pest Control Products* by Ravensberg (2011) is the first comprehensive attempt to analyze and communicate in a publically available single volume the entire process of developing products from entomopathogens. It is of particular value that examples were drawn from real product development projects and the author explains the regulatory and commercial challenges that may be unfamiliar to research scientists who are focused on biological studies, but that need to be addressed in developing research programs that will facilitate eventual commercialization.

Registration is often identified as the biggest barrier to commercialization of MCAs (Montesinos, 2003; Chandler et al., 2008; Ravensberg, 2011; Sundh et al., 2012a). The issues around registration of MCAs have been discussed extensively in three recent books that addressed ways to simplify registration and reduce the costs for MCA development (Bailey et al., 2010; Ehlers, 2011; Sundh et al, 2012b). MCAs must be regarded as living entities within an ecosystem rather than simply as replacements for chemical pesticides (Sundh andGoettel, 2013). Kabuluk et al. (2010) compared in detail many registration systems used worldwide. The particular issues of developing successful MCA products for Africa have also been explored in some detail (Cherry and Gwynn, 2007; Grzywacz et al., 2009).

7. Conclusions

Globally, pests annually consume the amount of food estimated to feed an additional one billion people (Birch et al., 2011). The human population is expected to grow from 6 billion today to 9 billion in 2050 and the amount of food produced must increase commensurately. Increased crop production will mean increased amounts of food available for pests, with pest population increases and higher pest pressure as a consequence.

The higher cost associated with the current generation of microbial pesticide products in comparison to most chemical insecticides is still considered a major limiting factor in many promising markets, especially in Asia and developing countries (Skovmand, 2007). The expanding global impact of Maximum Residue Limit regulations in removing older cheaper broad spectrum chemicals is expected to lower this barrier somewhat, although the ready availability of cheap "off patent" pesticides in many markets still constitutes a serious challenge to microbial pesticides.

Glare et al. (2012) contend that MCAs have not yet reached their full potential, even though all predictions suggest microbial pesticides will outperform other pest control options in terms of market share increases in the near future. While the outlook for most microbial products is more positive than it has been for many years, there are a number of generic issues that will determine how much use expands in the near to long term future.

Most MCAs are arthropod-specific, and most crops are likely to be affected by a suite of pests, therefore MCAs will need to be successfully integrated with other microbial products or pest management strategies in order to provide the pest control that farmers require. Several studies have been carried out to assess interactions of insect pathogens with chemical pesticides and fungicides. In general, few deleterious effects have been observed under field conditions and adverse effects observed in vitro were often not reliable predictors of antagonism under natural conditions. We cannot assume that all biocontrol agents, simply because they are living organisms, are compatible or interact positively, yet few studies have documented interactions among MCAs. The importance of such studies is evident, and clearly more research is needed to provide integrated, compatible, cost-effective and reliable bio-based pest control strategies for cropping systems, not only for individual crop pests. For example, synergistic virulence to the scarab, *Cyclocephala* spp., was observed for combinations of EPNs with *P. popilliae* (Thurston et al., 1993, 1994) or with *B. thuringiensis* subspecies *japonensis* (Koppenhöfer and Kaya, 1997; Koppenhöfer et al., 1999). However, interactions between entomopathogenic nematodes and other entomopathogens can also be antagonistic (Baur et al., 1998; Brinkman and Gardner, 2000; Koppenhöfer and Kaya, 1997; Shapiro-Ilan et al., 2004b). Advances in our understanding of infection processes, combined with the availability of new molecular tools that aid our ability to monitor the fate of entomopathogens in the environment and quantify effects of environmental factors on efficacy and persistence, continue to provide new insights that will support the rational development of these technologies.

Legislation to increasingly restrict the residues of chemical pesticides in agricultural produce (including flowers and non-food products), is providing a major thrust for farmers to adopt non-chemical controls in place of chemical pesticides. Consumer awareness and demand is also driving major produce retailers to force growers to implement more sustainable pest and disease management techniques. This is creating new market opportunities for microbials and resulting in the expansion of the range of microbial products available to farmers. There seems little doubt that over the next decade major new opportunities to expand the use of microbials in agriculture will occur.

However, while legislators are reducing the number of chemical pesticides and restricting their use, the regulatory agencies continue to operate in a regulatory framework for chemicals, which restricts progress by regulating microbial pesticides similarly to chemical insecticides. While there are moves to change regulations to create an easier pathway for the registration of biologicals, the current system remains a major impediment to the wider availability of microbial pesticides and their expanded use. Greater harmonization of registration practices across international boundaries, and acceptance of ‘generic’ safety data will help to streamline the registration process, and reduce the time and cost of bringing new microbial products to market.

Microbial products, even when effective, must be able to compete successfully with other non-chemical technologies such as cultural controls, predators and parasitoids, on both cost and ease of use. This requires that research focuses on improving production techniques to lower costs and on formulation to improve storage and use, as well as on persistence to reduce the need for frequent application. A major task is to ensure that quality products are available and that farmers are equipped with the knowledge to apply them. By focusing resources on transitional research to devise robust practices, microbial pesticides can become important components of integrated crop production systems.

8. Recommendations

Clear efforts must be made to engage stakeholders along the entire marketing chain including producers, regulators, farmers, retailers and consumers, to ensure acceptance and support of biocontrol approaches and the incorporation of MCAs in IPM strategies. Outreach and demonstration programs that promote understanding of what growers can (or cannot) expect from these control agents, coupled with appropriate training on their use, will further enhance their successful integration into agricultural production systems. Even though the climate for microbial pesticides is becoming more positive, significant research is still needed to overcome the limitations of current microbial products and expand the range of products available if they are to play a significantly greater role in the next generation of farming and pest control. Our recommendations to address these needs include:

1. Continue the search for new entomopathogens. Given the withdrawl of chemical pesticides, new and diverse host-specific and multi-host entomopathogens are urgently needed. Pathogens can provide new efficacious MCAs and also the genetic diversity needed for adaptation to a wider range of habitats and climates. New entomopathogens can also serve as sources of novel genes for insect resistance and other advantageous traits that can be incorporated into the genomes of other microorganisms or plants.
2. Continue development of production, formulations and application methods that will improve the efficacy, user acceptability and cost efficiency of MCAs for a variety of crops and climates.

3. Focus on strategic selections of target pests and markets to meet the challenge of developing non-chemical control of global pests, including disease vectors. Control of vectors of human, animal and plant diseases is a growing global public priority and MCA research needs to address these targets.
4. Continue development of transgenic plants using MCA genes for additional major crops. Develop objective and evidence-based knowledge to increase public understanding of transgenic crops.
5. Adopt streamlined registration procedures for MCAs and harmonize global registration systems.
6. Conduct further studies on the ecology of insect pathogens and their role in the environment, which will increase their potential for efficient and sustainable use in pest management.

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References

Abdel-Razek, A.S., 2010. Field evaluation of bacterial symbionts of entomopathogenic nematodes for suppression of hairy rose beetle, *Tropinota squalida* Scop., (Coleoptera: Scarabaeidae) population on cauliflower in Egypt. Archives of Phytopathology and Plant Protection 43, 18-25.

Abolins, S., Thind, B., Jackson, V., Luke, B., Moore, D., Wall, R., Taylor, M.A., 2007. Control of the sheep scab mite *Psoroptes ovis in vivo* and *in vitro* using fungal pathogens. Veterinary Parasitology 148, 310-317.

Abot, A.R., Moscardi, F., Fuxa, J.R., Sosa-Gómez, D.R., Richter, A.R., 1996. Development of resistance by *Anticarsia gemmatalis* from Brazil and United States to a nuclear polyhedrosis virus under laboratory selection pressure. Biological Control 7, 126–130.

Acevedo, J.P.M., Samuels, R.I., Machado, I.R., Dolinski, C., 2007. Interactions between isolates of the entomopathogenic fungus *Metarhizium anisopliae* and the entomopathogenic nematode *Heterorhabditis bacteriophora* JPM4 during infection of the sugar cane borer *Diatraea saccharalis* (Lepidoptera: Pyralidae). Journal of Invertebrate Pathology 96, 187-192.

Adams, B.J., Nguyen, K.B., 2002. Taxonomy and systematics. In: Gaugler, R. (Ed.), Entomopathogenic Nematology. CABI, Wallingford, UK, pp 1-34.

Adhikari, B.N., Chin-Yo, L., Xiaodong, B., Ciche, T.A., Grewal, P.S., Dillman, A.R., Chaston, J.M., Shapiro-Ilan, D.I., Bilgrami, A.L., Gaugler, R., Sternberg, P.W., Adams, B.J., 2009. Transcriptional profiling of trait deterioration in the insect pathogenic nematode *Heterorhabditis bacteriophora.* BMC Genomics 10, 609.

Adjei, M.B., Smart, G.C. Jr., Frank, J.H., Leppla, N.C., 2006. Control of pest mole crickets (Orthoptera: Gryllotalpidae) in bahiagrass pastures with the nematode *Steinernema scapterisci* (Rhabditida: Steinernematidae). Florida Entomologist 89, 532-535.

Adler, P.H., McCreadie, J.W., 2009. Black flies (Simuliidae). In: Mullen, G.R., Durden, L.A. (Eds.), Medical and Veterinary Entomology, 2nd Edition. Academic Press, San Diego, CA, USA, pp. 183-200.

Adler, P.H., Currie, D.C., Wood, D.M., 2004. The Black Flies (Simuliidae) of North America. Cornell University Press, Ithaca, NY, USA, pp. 941.

Akello, J.T., Dubois, T., Gold, C.S., Coyne, D., Nakavuma J., Paparu, P., 2007. *Beauveria bassiana* (Balsamo) Vuillemin as an endophyte in tissue culture banana (*Musa* spp.). Journal of Invertebrate Pathology 96, 34-42.

Akhurst, R., Smith, K., 2002. Regulation and safety. In: Gaugler, R. (Ed.), Entomopathogenic Nematology. CABI, Wallingford, UK, pp. 311-332.

Al-mazra'awi, M.S., Shipp, J.L., Broadbent, A.B., Kevan, P.G., 2006a. Dissemination of *Beauveria bassiana* by honey bees (Hymenoptera: Apidae) for control of tarnished plant bug (Hemiptera: Miridae) on canola. Environmental Entomology 35, 1569-1577.

Al-mazra'awi, M.S., Shipp, J.L., Broadbent, A.B., Kevan, P.G., 2006b. Biological control of *Lygus lineolaris* (Hemiptera: Miridae) and *Frankliniella occidentalis* (Thysanoptera: Thripidae) by *Bombus impatiens* (Hymenoptera: Apidae) vectored *Beauveria bassiana* in greenhouse sweet pepper. Biological Control 37, 89-97.

Al-Mazra'awi, M.S., Kevan, P.G., Shipp, J.L., 2007. Development of *Beauveria bassiana* dry formulation for vectoring by honey bees *Apis mellifera* (Hymenoptera: Apidae) to the flowers of crops for pest control. Biocontrol Science and Technology 17, 733-741.

Alcázar, J., Cervantes, M., Raman, K.V., 1992. Efectividad de un virus granulosis formulado en polvo para controlar *Phthorimaea* en papa almacenada. Revista Peruana de Entomología 35, 113-116.

Ali, J.G., Campos-Herrera, R., Alborn, H.T., Duncan, L.W., Stelinski, L.L., 2013. Sending mixed messages: A trophic cascade produced by a belowground herbivore-induced cue. Journal of Chemical Ecology 39, 1140-1147.

Alm, S.R., Villani, M.G., Yeh, T., Shutter, R., 1997. *Bacillus thuringiensis* serovar *japonensis* strain *Buibui* for control of Japanese and Oriental Beetle Larvae (Coleoptera: Scarabaeidae). Applied Entomology and Zoology 32, 477-484.

Alston, D. G., Rangel, D. E. N., Lacey, L.A., Golez, H.G., Kim, J.J., Roberts, D.W., 2005. Evaluation of novel fungus and nematode isolates for control of *Conotrachelus nenuphar* (Coleoptera: Curculionidae) larvae. Biological Control 35, 163–171.

Alves, S.B., Lopes, R.B. (Eds.), 2008. Controle Micobiano de Pragas na América Latina: avanços e desafios. Fundação de Estudos Agrários Luiz de Queiroz, Piracicaba, Brasil, pp. 414.

Alves, L.F.A., Batista-Filho, A., Augusto, B.N.T., 2001. Fotoprotección de preparaciones del virus de la poliedrosis nuclear (VPNAg) en condiciones de campo y laboratorio. Manejo Integrado de Plagas 62, 60-64.

Alves, S.B., Lopes, R.B., Vieira, S.A., Tamai, M.A., 2008. Fongos entomopatogênicos usados no controle de pragas na América Latina. In: Alves, S.B., Lopes, R.B. (Eds.), Controle Micobiano de Pragas na América Latina: avanços e desafios. Fundação de Estudos Agrários Luiz de Queiroz, Piracicaba, Brasil, pp. 69-110.

An, R., Grewal, P.S., 2007. Differences in the virulence of *Heterorhabditis bacteriophora* and *Steinernema scarabaei* to three white grub species: The relative contribution of the nematodes and their symbiotic bacteria. Biological Control 43, 310-316.

Anbesse, S., Sumaya, N.H., Dörfler, A.V., Strauch, O., Ehlers, R.-U., 2013. Selective breeding for desiccation tolerance in liquid culture provides genetically stable inbred lines of the entomopathogenic nematode *Heterorhabditis bacteriophora*. Applied Microbiology and Biotechnology 97, 731-739.

Andermatt Biocontrol. 2014. Product portfolio 2014. http://www.export.biocontrol.ch/media/pdf/home/andermatt_biocontrol_product_portfolio.pdf. (Accessed January 20 2014)

Anderson, P.L., Hellmich, R.L. II, Prasifka, J.R., Lewis, L.C., 2005. Effects on fitness and behavior of monarch butterfly larvae exposed to a combination of Cry1ab-expressing corn anthers and pollen. Environmental Entomology 34, 944–952.

Ansari, M.A., Tirry, L., Moens, M., 2004. Interaction between *Metarhizium anisopliae* CLO 53 and entomopathogenic nematodes for the control of *Hoplia philanthus*. Biological Control 31, 172-180.

Ansari, M.A., Shah, F.A., Tirry, L., Moens, M., 2006a. Field trials against *Hoplia philanthus* (Coleoptera: Scarabaeidae) with a combination of an entomopathogenic nematode and the fungus *Metarhizium anisopliae* CLO 53. Biological Control 39, 453-459.

Ansari, M.A., Shah, F.A., Whittaker, M., Prasad, M., Butt, T.M., 2006b. Control of western flower thrips (*Frankliniella occidentalis*) pupae with *Metarhizium anisopliae* in peat and peat alternative growing media. Biological Control 40, 293-297.

Ansari, M.A., Shah, F.A., Butt, T.M., 2008a. Combined use of entomopathogenic nematodes and *Metarhizium anisopliae* as a new approach for black vine weevil, *Otiorhynchus sulcatus* (Coleoptera: Curculionidae) control. Entomologia Experimentalis et Applicata 129, 340-347.

Ansari, M.A., Brownbridge, M., Shah, F.A., Butt, T.M., 2008b. Efficacy of entomopathogenic fungi against soil-dwelling stages of western flower thrips, *Frankliniella occidentalis*, in plant-growing media. Entomologia Experimentalis et Applicata 127, 80-87.

Ansari, M.A., Hussain, M.A., Moens, M., 2009. Formulation and application of entomopathogenic nematode-infected cadavers for control of *Hoplia philanthus* in turfgrass. Pest Management Science 65, 367-374.

Ansari, M.A., Shah, F.A., Butt, T.M., 2010. The entomopathogenic nematode *Steinernema kraussei* and *Metarhizium anisopliae* work synergistically in controlling overwintering larvae of the black vine weevil, *Otiorhynchus sulcatus*, in strawberry growbags. Biocontrol Science and Technology 20, 99–105.

Ansell, C., 2008. Pesticide Regulation in the EU and California. UC Berkeley: Institute of Governmental Studies. Retrieved from: http://escholarship.org/uc/item/7h47100

Aranda, E., Lorence, A., del Refugio Trejo, M., 2000. Rural production of Bacillus thuringiensis by solid state fermentation. . In: Charles, J.-F., Delecluse, A., Nielsen-LeRoux, C. (Eds.), Entomopathogenic Bacteria: from laboratory to field application. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 317-332.

Arrizubieta, M., Williams, T., Caballero, P., Sim´on, O. 2014. Selection of a nucleopolyhedrovirus isolate from *Helicoverpa armigera* as the basis for a biological insecticide. Pesticide Management Science, (in press) DOI 10.1002/ps.3637.

Arthurs, S., Lacey, L.A., Fritts, R. Jr. 2005. Optimizing the use of the codling moth granulovirus:

effects of application rate and spraying frequency on control of codling moth larvae in Pacific Northwest apple orchards. Journal of Economic Entomology 98, 1459-1468.

Arthurs, S.P., Lacey, L.A., Behle, R.W., 2006. Evaluation of spray-dried lignin-based formulations and adjuvants as ultraviolet light protectants for the granulovirus of the codling moth, *Cydia pomonella* (L). Journal of Invertebrate Pathology 93, 88–95.

Arthurs, S.P., Hilton, R., Knight, A.L., Lacey, L.A., 2007. Evaluation of the pear ester kairomone as a formulation additive for the granulovirus of codling moth, *Cydia pomonella* (Lepidoptera: Tortricidae) in pome fruit. Journal of Economic Entomology 100, 702-709.

Arthurs, S., Lacey, L.A., Behle, R.W. 2008a. Evaluation of lignins and particle films as solar protectants for the granulovirus of the codling moth, *Cydia pomonella* L. Biocontrol Science and Technology 18: 829-839.

Arthurs, S.P., Lacey, L.A., de la Rosa, F., 2008b. Evaluation of a granulovirus (PoGV) and *Bacillus thuringiensis* subsp. *kurstaki* for control of the potato tuberworm in stored tubers. Journal of Economic Entomology 101, 1540-1546.

Arthurs, S.P., Lacey, L.A., Pruneda, J.N., Rondon, S., 2008c. Semi-field evaluation of a granulovirus and *Bacillus thuringiensis* ssp. *kurstaki* for season-long control of the potato tuber moth, *Phthorimaea operculella.* Entomologia Experimentalis et Applicata 129, 276-285.

Asano, S., 2005. Ultraviolet protection of a granulovirus product using iron oxide. Applied Entomology and Zoology 40, 359-364.

Asser-Kaiser, S., Fritch, E., Undorf-Spahn, K., Kienzle, J., Eberle, K. E., Gund, N.A., Reineke, A., Zebitz, C.P., Heckel, D.G., Huber, J., Jehle, J.A., 2007. Rapid emergence of baculovirus resistance in codling moth due to dominant, sex linked inheritance. Science 317, 1916-1918.

Asser-Kaiser, S., Radtke, P., El-Salamouny, S., Winstanley, D., Jehle, J.A., 2011. Baculovirus resistance in codling moth (*Cydia pomonella* L.) caused by early block of virus replication. Virology 410, 360–367.

Athanassiou, C.G., Palyvos, N.E., Kakouli-Duarte, T., 2008. Insecticidal effect of *Steinernema feltiae* (Filipjev) (Nematoda: Steinernematidae) against *Tribolium confusum* du Val (Coleoptera: Tenebrionidae) and *Ephestia kuehniella* (Zeller) (Lepidoptera: Pyralidae) in stored wheat. Journal of Stored Product Research 44, 52-57.

Backman, P.A., Sikora, R.A., 2008. Endophytes: An emerging tool for biological control. Biological Control 46, 1-3.

Bai, C., Shapiro-Ilan, D.I., Gaugler, R., Hopper, K.R., 2005. Stabilization of beneficial traits in *Heterorhabditis bacteriophora* through creation of inbred lines. Biological Control. 32, 220-227.

Bai, X., Grewal, P.S., 2007. Identification of two down-regulated genes in entomopathogenic nematode *Heterorhabditis bacteriophora* infective juveniles upon contact with insect hemolymph. Molecular and Biochemical Parasitology 156, 162-166.

Bai, X., Adams, B.J., Ciche, T.A., Clifton, S., Gaugler, R., Hogenhout, S.A., Spieth, J., Sternberg, P.W., Wilson, R.K., Grewal, P.S., 2009. *Transcriptomic analysis of the entomopathogenic nematode Heterorhabditis bacteriophora TTO1.* BMC Genomics 10, 205.

Bai, X., Adams, B.J., Ciche, T.A., Clifton, S., Gaugler, R., Kim, K.-S., Spieth, J., Steinberg, P.W., Wilson, R.K., Grewal, P.S., 2013. .A lover and a fighter: The genome sequence of an entomopathogenic nematode *Heterorhabditis bacteriophora*. *PLoS ONE* 8 (7), art. no. 69618

Bailey, A., Chandler, D., Grant, W.P., Greaves, J., Prince, G., Tatchell, M. 2010. Biopesticides: Pest Management and Regulation. CABI International, Wallingford. 232pp.

Ballard, J., Ellis, D.J., Payne C.C., 2000a. Uptake of granulovirus from the surface of apples and leaves by first instar larvae of the codling moth *Cydia pomonella* L. (Lepidoptera: Olethreutidae). Biocontrol Science and Technology, 10, 617-625.

Ballard, J., Ellis, D.J., Payne, C.C., 2000b. The role of formulation additives in increasing the potency of *Cydia pomonella* granulovirus for codling moth larvae, in laboratory and field experiments. Biocontrol Science and Technology 10, 627-640.

Bandani, A.R., Khambay, B.P.S., Faull, J.L., Newton, R., Deadman, M., Butt, T.M., 2000. Production of efrapeptins by *Tolypocladium* species and evaluation of their insecticidal and antimicrobial properties. Mycological Research 104, 537-544.

Barbara, K.A., Buss, E.A., 2006. Augmentative applications of *Steinernema scapterisci* (Nematoda: Steinernematidae) for mole cricket (Orthoptera: Gryllotalpidae) control on golf courses. Florida Entomologist 89, 257-262.

Bateman, R., 2004. Constraints and enabling technologies for mycopesticide development. Outlooks on Pest Management 15, 64-69.

Bauce, E., Carissey, N., Dupont, A., van Frankenhuyzen, K., 2004. *Bacillus thuringiensis* subsp. *kurstaki* aerial spray prescriptions for balsam fir stand protection against spruce budworm (Lepidoptera: Tortricidae). Journal of Economic Entomology 97, 1624-1634.

Bauer, L.S., 1992. Response of the imported willow leaf beetle to *Bacillus thuringiensis* var. *san diego* on poplar and willow. Journal of Invertebrate Pathology 59, 330-331.

Baverstock, J., Roy, H.E., Pell, J.K., 2010. Entomopathogenic fungi and insect behaviour: from unsuspecting hosts to targeted vectors. BioControl 55, 89-102.

Bedding, R.A., 2008. Controlling the pine-killing woodwasp, *Sirex noctilio*, with nematodes. In: Hajek, A.E., Glare, T.R., O'Callaghan, M. (Eds.), Use of Microbes for Control and Eradication of Invasive Arthropods. Springer, Dordrecht, The Netherlands, pp. 213-235.

Beegle, C.C., Yamamoto, T., 1992. History of *Bacillus thuringiensis* Berliner research and development. Canadian Entomologist 124, 587-616.

Beegle, C. C., R. I. Rose, R. I., Ziniu, Y., 1991. Mass production of *Bacillus thuringiensis* and *B. sphaericus* for microbial control of insect pests. In: Maramorosch, K., (ed.) Biotechnology for Biological Control of Pests and Vectors. CRC Press, Boca Raton. pp. 195-216.

Behie, S.W., Zelisko, P.M., Bidochka, M.J., 2012. Endophytic insect-parasitic fungi translocate nitrogen directly from insects to plants. Science 22, 1576-1577.

Behle, R., Birthisel, T. 2014. Formulation of entomopathogens as bioinsecticides. In: Morales-Ramos, J.A., Guadalupe Rojas, M., Shapro-Ilan D.L. (Eds.) Mass production of beneficial organisms. Elsevier, Amsterdam. pp 483-517.

Behle R .W., Popham., H.J.R. 2012. Laboratory and field evaluations of efficacy of a fast killing baculovirus isolate from Spodoptera frugiperda. Journal of Invertebrate Pathology 109, 194-200.

Behle, R.W., Tamez-Guerra, P., McGuire, M.R., 2003. Field activity and storage stability of *Anagrapha falcifera* nucleopolyhedrovirus (AfMNPV) in spray-dried lignin-based formulations. Journal of Economic Entomology 96 1066-1075.

Belloncik, S., Mori, H., 1998. Cypoviruses. In: Miller, L.K., Ball, A.L. (Eds.), The Insect Viruses. Plenum Press, New York, pp 337-364.

Bellotti, A.C., Smith, L., Lapointe, S. L., 1999. Recent advances in cassava pest management. Annual Review of Entomology 44, 343-370.

Belur, P.D., Inman III, F.L., Holmes, L.D., 2013. Determination of specific oxygen uptake rate of *Photorhabdus luminescens* during submerged culture in lab scale bioreactor. Biocontrol Science and Technology 23, 1458-1468.

Berger, P., Hauxwell, C., Murray, D., 2007. Nucleopolyhedrovirus introduction in Australia. Virologica Sinica 22, 173-179.

Bergoin, M., Tijssen, P., 1998. Biological and molecular properties of densoviruses and their use in protein expression and biological control. In: Miller, L.K., Ball, L.A. (Eds.), The Insect Viruses. Plenum, New York, pp. 141-169.

Bernstein, J.A., Bernstein, I.M., Bucchini, L., Goldman, L.R., Hamilton, R.G., Lehrer, S., Rubin, C., Sampson, H. A., 2003. Clinical and laboratory investigation of allergy to genetically modified foods. Environmental Health Perspectives 111, 1114-1121.

Bidochka, M.J., Kamp, A.M., Lavender, T.M., Dekoning, J., De Croos, J.N.A., 2001. Habitat association in two genetic groups of the insect pathogenic fungus *Metarhizium anisopliae*: Uncovering cryptic species? Applied and Environmental Microbiology 67, 1335-1342.

Bidochka, M.J., Menzies, F.V., Kamp, A.M., 2002. Genetic groups of the insect-pathogenic fungus *Beauveria bassiana* are associated with habitat and thermal growth preferences. Archives in Microbiology 178, 531-537.

Bielza, P., Denholm, I., Sterk, G., Leadbeater, A., Leonard, P., Jørgensen, L. N., 2008. Declaration of Ljubljana - The impact of a declining European pesticide portfolio on resistance management. Outlooks on Pest Management 19, (6), 246-248.

Bilgrami, A.L, Gaugler, R., Shapiro-Ilan, D.I., Adams, B.J., 2006. Source of trait deterioration in entomopathogenic nematodes *Heterorhabditis bacteriophora* and *Steinernema carpocapsae* during *in vivo* culture. Nematology 8, 397-409.

Birch, A.N.E., Begg, G.S., Squire, G.R. 2011. How agro-ecological research helps to address food security issues under new IPM and pesticide reduction policies for global crop production systems. Journal of Experimental Botany 62, 3251–3261.

Bird, A. E., Hesketh, H., Cross, J. V., Copland, M., 2004. The common black ant, *Lasius niger* (Hymenoptera: Formicidae), as a vector of the entomopathogen *Lecanicillium longisporum* to rosy apple aphid, *Dysaphis plantaginea* (Homoptera: Aphididae). Biocontrol Science and Tecnology 14, 757-767.

Bischoff, J.F., Rehner, S.A., Humber, R.A., 2009. A multilocus phylogeny of the *Metarhizium anisopliae* lineage. Mycologia 101, 512–530.

Bixby, A., Alm, S.R., Power, K., Grewal, P., Swier, S., 2007. Suscepbitlity of four pecies of turfgrass-infesting scarabs (Coleopertra: Scarabaeidae) to *Bacillus thuringiensis* serovar *japonensis* strain *Buibui*. Journal of Economic Entomology 100, 1604-1610.

Bixby-Brosi, A.J., Potter D.A., 2010. Evaluating a naturally occurring baculovirus for extended biological control of the black cutworm (Lepidoptera:Noctuidae) in golf course habitats. Journal of Economic Entomology, 103, 1555-1563.

Black, B.C., Brennan, L.A., Dierks, P.M., Gard, I.E., 1997. Commercialisation of baculovirus insecticides. In: Miller, L.K. (Ed.), The Baculoviruses. Plenum press, New York, pp. 341-387.

Blackwell, M., 2010. Fungal evolution and taxonomy. BioControl 55, 7-16.

Blanford, S., Chan, B.H.K., Jenkins, N., Sim, D., Turner, R.J., Read, A.F., Thomas, M.B., 2005. Fungal pathogen reduces potential for malaria transmission. Science 308, 1638-1641.

Blanford, S., Read, A., Thomas, M.B., 2009. Thermal behavior of *Anopheles stephensi* in response to infection with malaria and fungal entomopathogens. Malaria Journal 8, 72.

Blommers, L.H.M., 1994. Integrated pest management in European apple orchards. Annual Review of Entomology 39, 213-41.

Bonning, B.C., Boughton, J.A., Jin, H., Harrison, R.L., 2002. Genetic enhancement of baculovirus insecticides. In: Upadhyay, K. (Ed.), Advances in Microbial Control of Insect Pests. Kluwer Academic, Plenum, New York, pp 109-126.

Boonserm, P., Davis, P., Ellar, D.J., Li, J., 2005. Crystal Structure of the mosquito-larvicidal toxin Cry4Ba and its biological implications. Journal of Molecular Biology 348, 363–382.

Boonserm, P., Mo, M., Angsuthanasombat, C., Lescar, J., 2006. Structure of the functional form of the mosquito larvicidal Cry4Aa toxin from *Bacillus thuringiensis* at a 2.8-Å resolution. Journal of Bacteriology 188, 3391–3401.

Böszörmènyi, E., Ersek, T., Fodor, A., Fodor, A.M., Foldes, L.S., Hevesi, M., Hogan, J.S., Katona, Z., Klein, M.G., Kormany, A., Pekar, S., Szentirmai, A., Sztaricskai, F., Taylor, R.A.J., 2009. Isolation and activity of *Xenorhabdus* antimicrobial compounds against the plant pathogens *Erwinia amylovora* and *Phytophthora nicotianae*. Journal of Applied Microbiology 107, 746–759.

Bourner, T.C., Cory, J.S., 2004. Host range of an NPV and a GV isolated from the common cutworm, *Agrotis segetum*: pathogenicity within the cutworm complex. Biological Control 31, 372-379.

Bravo, A., Gómez, I., Conde, J., Muñoz-Garay, C., Sánchez, J., Miranda, R., Zhuang, M., Gill, S.S., Soberón, M., 2004. Oligomerization triggers binding of a *Bacillus thuringiensis* Cry1Ab pore-forming toxin to aminopeptidase N receptor leading to insertion into membrane microdomains. Biochimica et Biophysica Acta 1667, 38-46.

Bravo, A., Gill, S.S., Soberon M., 2007. Mode of action of *Bacillus thuringiensis* Cry and Cyt toxins and their potential for insect control. Toxicon 49, 423–435.

Bravo, A., Likitvivatanavong, S., Gill, S.S., Soberón, M., 2011. *Bacillus thuringiensis*: A story of a successful bioinsecticide. Insect Biochemistry and Molecular Biology 41, 423-431.

Brookes, G., and Barfoot, P. 2013. GM Crops: Global Socio-Economic and Environmental Impacts 1996-2011. PG Economics Ltd, UK, pp. 191.

Brown, I.M., Shapiro-Ilan, D.I., Gaugler, R., 2006. Entomopathogenic nematode infectivity enhancement using physical and chemical stressors. Biological Control 39, 147-153.

Brownbridge, M., 2006. Entomopathogenic fungi: Status and considerations for their development and use in integrated pest management. Recent Research Developments in Entomology 5, 27-58.

Brownbridge, M., Glare, T., 2007. Impact of entomopathogenic fungi on soil-dwelling invertebrates. In: Ekesi, S., Maniania, N.K. (Eds.), Use of Entomopathogenic Fungi in Biological Pest Management. Research Signpost, Kerala, India, pp 295-312.

Brownbridge, M., Costa, S., Jaronski, S.T., 2001. Effects of *in vitro* passage of *Beauveria bassiana* on virulence to *Bemisia tabaci*. Journal of Invertebrate Pathology 77, 280-283.

Brownbridge, M., Nelson, T.L., Hackell, D.L., Eden, T.M., Wilson, D.J., Willoughby, B.E., Glare, T.R., 2006. Field application of biopolymer-coated *Beauveria bassiana* F418 for clover root weevil (*Sitona lepidus*) control in Waikato and Manawatu. New Zealand Plant Protection 59, 304-311.

Brownbridge, M., Townsend, R.J., O'Callaghan, M., Bell, N.L., Mander, C., Jackson, T.A., 2008. Developing opportunities for entomopathogenic microbes and nematodes in crop protection. In: Butcher, M.R., Walker, J.T.S., Zydenbos, S.M. (Eds.), Future Challenges in Crop Protection: Repositioning New Zealand's Primary Industries for theFfuture. New Zealand Plant Protection Society, Inc., pp 129-142.

Broza, M., Pereira, R.M., Stimac, J.L., 2001. The nonsusceptibility of soil Collembola to insect pathogens and their potential as scavengers of microbial pesticides. Pedobiologia 45, 523-534.

Bruck, D.J., 2005. Ecology of *Metarhizium anisopliae* in soilless potting media and the rhizosphere: implications for pest management. Biological Control 32, 155-163.

Bruck, D.J., 2010. Fungal entomopathogens in the rhizosphere. BioControl 55, 103-112.

Bruck, D.J., Walton, V.M., 2007. Susceptibility of the filbertworm (*Cydia latiferreana*, Leptidoptera: Tortricidae) and filbert weevil (*Curculio occidentalis*, Coleoptera: Curculionidae) to entomopathogenic nematodes. Journal of Invertebrate Pathology 96, 93-96.

Bruck, D.J., Shapiro-Ilan, D.I., Lewis, E.E., 2005. Evaluation of application technologies of entomopathogenic nematodes for control of the black vine weevil, *Otiorhynchus sulcatus*. Journal of Economic Entomology 98, 1884-1889.

Brusselman, E. Beck, B., Pollet, S., Temmerman, F., Spanoghe, P., Moens, M., Nuyttens, D., 2012. Effect of the spray application technique on the deposition of entomopathogenic nematodes in vegetables. Pest Management Science 68, 444–453.

Bucchini, L., Goldman, L.R., 2002. Starlink corn: a risk analysis. Environmental Health Perspectives 110, 5-13.

Buerger, P., Hauxwell, C., Murray, D., 2007. Nucleopolydrovirus introduction in Australia. Virologica Sinica 22,173-179.

Buitenhuis, R., Shipp, J.L., 2006. Factors influencing the use of trap plants for the control of *Frankliniella occidentalis* (Thysanoptera: Thripidae) on greenhouse potted chrysanthemum. Environmental Entomology 35, 1411-1416.

Burdan, J.P., Hails, R.S., Windass, J.D., Suner, M. M., Cory, J.S., 2000. Infectivity, speed of kill and productivity of a baculovirus expressing the itch mite toxin txp-1 in a second and forth instar of *Trichoplusia ni*. Journal of Invertebrate Pathology 75, 226-236.

Burges, H.D., 2007. Techniques for testing microbials for control arthropod pests in greenhouses. In: Lacey, L.A., Kaya, H.K. (Eds.), Field Manual of Techniques in Invertebrate Pathology: Application and Evaluation of Pathogens for Control of Insects and Other Invertebrate Pests, 2nd Edition. Springer, Dordrecht, The Netherlands, pp. 463-479.

Burges, H.D., Jones, K.A., 1998. Formulation of bacteria, viruses and protozoa to control insects. In: Burges, H.D. (Ed.), Formulation of Microbial Biopesticides. Kluwer Academic Publishers, Dordrecht, pp 33-127.

Burnell, A., 2002. Genetics and genetic improvement. In: Gaugler, R. (Ed.), Entomopathogenic Nematology. CABI, Wallingford, UK, pp 333-356.

Bussaman, P., Sermswan, R.W., Grewal, P.S., 2006. Toxicity of the entomopathogenic bacteria *Photorhabdus* and *Xenorhabdus* to the mushroom mite (*Luciaphorus* sp.; Acari: Pygmephoridae). Biocontrol Science and Technology 16, 245-256.

Butt, T.M., Goettel, M.S., 2000. Bioassays of entomogenous fungi. In: Navon, A., Ascher, K.R.S. (Eds.), Bioassays of Entomopathogenic Microbes and Nematodes. CABI International Press, Wallingford, U.K., pp 141-195.

Butt, T.M., Carreck, N.L., Ibrahim, L., Williams, I.H., 1998. Honey-bee-mediated infection of pollen beetle (*Meligethes aeneus* Fab.) by the insect-pathogenic fungus, *Metarhizium anisopliae*. Biocontrol Science and Technology 8, 533-538.

Cadogan, B.L., Scharbach, R.D., Brown, K.W., Ebling, P.M., Payne, N.J., Krause, R.E., 2004. Experimental aerial application of a new isolate of nucleopolyhedrovirus, CfMNPV against *Choristoneura fumiferana* (Lepidoptera: Tortricidae). Crop Protection 23, 1-9.

Campbell, J.F., Kaya, H.K., 1999. How and why a parasitic nematode jumps. Nature 397, 485-486.

Campbell, J.F., Kaya, H.K., 2002. Variation in entomopathogenic nematode (Steinernematidae and Heterorhabditidae) infective stage jumping behavior. Nematology 4, 471-482.

Campbell, J.F., Koppenhöfer, A.M., Kaya, H.K., Chinnasri, B., 1999. Are there temporarily non-infectious dauer stages in entomopathogenic nematode populations: a test of the phased infectivity hypothesis. Parasitology 118, 499-508.

Campbell, L.G., Boetel, M.A., Jonason, N.B., Jaronski, S.T., Smith, L.J., 2006. Grower-adoptable formulations of the entomopathogenic fungus *Metarhizium anisopliae* (Ascomycota: Hypocreales) for sugarbeet root maggot (Diptera: Ulidiidae) management. Environmental Entomology 3, 986-991.

Campos-Herrera, R., Trigo, D., Gutièrrez, C., 2006. Phoresy of the entomopathogenic nematode *Steinernema feltiae* by the earthworm, *Eisenia fetida*. Journal of Invertebrate Pathology 92, 50-54.

Caprio, M. A., Sumerford, D. V., 2007. Evaluating transgenic plants for suitability in pest and resistance management programs. In: Lacey, L.A., Kaya, H.K. (Eds.), Field Manual of Techniques in Invertebrate Pathology: Application and Evaluation of Pathogens for Control of Insects and Other Invertebrate Pests, 2nd Edition. Springer, Dordrecht, The Netherlands. pp. 769-789.

Carneiro, R. M. D. G., Souza, I. S., Belarmino, L. C., 1998. Nematicidal activity of *Bacillus* spp. strains on juveniles of *Meloidogyne javanica*. Nematologia Brasileira 22, 12-21.

Castillejos, V., Trujillo, J., Ortega, L.D., Antonio-Santizo, J., Cisneros, J., Penagos, D.I., Valle, J., Williams, T., 2002. Granular phagostimulant nucleopolyhedrovirus formulations for control of *Spodoptera frugiperda* in maize. Biological Control 24, 300-310.

Castrillo, L.A., Vandenberg, J.D., Wraight, S.P., 2003. Strain-specific detection of introduced *Beauveria bassiana* in agricultural fields by use of sequence-characterized amplified region markers. Journal of Invertebrate Pathology 82, 75-83.

Castrillo, L. A., Griggs, M. H., Vandenberg, J. D., 2008. Quantitative detection of *Beauveria bassiana* GHA (Ascomycota: Hypocreales), a potential microbial control agent of the emerald ash borer, by use of real-time PCR. Biological Control 45: 163–169.

CDC, 2001. National Center for Environmental Health. Investigation of Human Health Effects Associated with Potential Exposure to Genetically Modified Corn: A Report to the U.S. Food and Drug Administration from the Centers for Disease Control and Prevention. Atlanta, GA

Chambers, U., Bruck, D.J., Olsen, J., Walton, V.M., 2010. Control of overwintering filbertworm (Lepidoptera: Tortricidae) larvae with *Steinernema carpocapsae*. Journal of Economic Entomology 103, 416- 422.

Chandler, D., Davidson, G., 2005. Evaluation of entomopathogenic fungus *Metarhizium anisopliae* against soil-dwelling stages of cabbage maggot (Diptera: Anthomyiidae) in glasshouse and field experiments and effect of fungicides on fungal activity. Journal of Economic Entomology 98, 1856-1862.

Chandler, D., Davidson, G., Pell, J.K., Ball, B.V., Shaw, K., Sunderland, K.D., 2000. Fungal biocontrol of Acari. Biocontrol Science and Technology 10, 357-384.

Chandler, D., Davidson, G., Jacobson, R.J., 2005. Laboratory and glasshouse evaluation of entomopathogenic fungi against the two-spotted spider mite, *Tetranychus urticae* (Acari: Tetranychidae), on tomato, *Lycopersicon esculentum*. Biocontrol Science and Technology 15, 37-54.

Chandler, D., Davidson, G., Grant, W.P., Greaves, J., Tatchell, G.M., 2008. Microbial biopesticides for integrated crop management: an assessment of environmental and regulatory sustainability. Trends in Food Science and Technology 19, 275-283.

Charles, J. F., Nielsen-LeRoux, C., Delécluse, A., 1996. *Bacillus sphaericus* toxins: molecular biology and mode of action. Annual Review of Entomology 41, 451-472.

Charles, J.-F., Silva-Filha, M.H., Nielsen-LeRoux, C., Humphreys, M.J., Berry, C., 1997. Binding of the 51- and 42-kDa individual components from the *Bacillus sphaericus* crystal toxin to mosquito larval midgut membranes from *Culex* and *Anopheles* sp. (Diptera: Culicidae). FEMS Microbiology Letters 156, 153-159.

Charles, J.-F., Delecluse, A., Nielsen-LeRoux, C. (Eds.), 2000. Entomopathogenic Bacteria: From Laboratory to Field Application. Kluwer Academic Publishers, Dordrecht, The Netherlands. 524 pp.

Charmillot, P.J., Pasquier, D., Scalo, A., 1998. Le virus de la granulose du carpocapse *Cydia pomonella*: 2. Efficacité en microparcelles, rémanence et rôle des adjuvants. Revue Suisse de Viticulture Arboriculture et Horticulture 30, 61-64.

Charnley, A.K., 2003. Fungal pathogens of insects: cuticle degrading enzymes and toxins. Advances in Botanical Research 40, 241-321.

Charnley, A.K., Collins, S.A., 2007. Entomopathogenic fungi and their role in pest control. In: Kubicek, C.P., Druzhinina, I.S. (Eds.), Environmental and Microbial Relationships, 2nd Edition: The Mycota IV. Springer-Verlag, Berlin, pp 159-187.

Chaston, J.M., Murfin, K.E., Heath-Heckman, E.A., Goodrich-Blair, H., 2013. Previously unrecognized stages of species-specific colonization in the mutualism between *Xenorhabdus* bacteria and *Steinernema* nematodes. Cellular Microbiology 15, 1545-1559.

Chavarria-Hernandez, N., de la Torre, M., 2001. Population growth kinetics of the nematode, *Steinernema feltiae*, in submerged liquid culture. Biotechnology Letters 23, 311-315.

Chavarria-Hernandez, N., Espino-Garcia, J.-J., Sanjuan-Galindo, R., Rodriguez-Hernandez, A.-I., 2006. Monoxenic liquid culture of the entomopathogenic nematode *Steinernema carpocapsae* using a culture medium containing whey kinetics and modeling. Journal of Biotechnology 125, 75-84.

Chavarria-Hernandez, N., Islas-López, M.-A., Vergara-Maciel, G., Gayosso-Canales, M., Rodriguez-Hernandez, A.-I., 2008. Kinetics of infective juvenile production of the entomopathogenic nematode *Steinernema carpocapsae* in submerged monoxenic culture. Bioprocess and Biosystems Engineering 31, 419-426.

Chen, J., Abawi, G. S., Zuckerman, B. M., 2000. Efficacy of *Bacillus thuringiensis*, *Paecilomyces marquandii*, and *Streptomyces costaricanus* with and without organic amendments against *Meloidogyne hapla* infecting lettuce. Journal of Nematology 32, 70–77.

Chen, M., Zhao, J.Z., Collins, H.L. Cao, J., Shelton, A.M., 2008. A critical assessment of the effects of Bt transgenic plants on parasitoids. PLoS One 3, e2284.

Chen, S., Glazer, I., Gollop, N., Cash, P., Argo, E., Innes, A., Stewart, E., Davidson, I., Wilson, M.J., 2006. Proteomic analysis of the entomopathogenic nematode *Steinernema feltiae* IS-6 IJs under evaporative and osmotic stresses. Molecular and Biochemical Parasitology 145, 195-204.

Cherry, A.J., Gwynn, R.L., 2007. Perspective on the development of biocontrol in Africa. Biocontrol Science and Technology 17, 665-676.

Cherry, A.J., Rabindra, R.J., Parnell, M.A., Geetha, N., Kennedy, J.S., Grzywacz, D., 2000. Field evaluation of *Helicoverpa armigera* nucleopolyhedrovirus formulations for control of the chickpea pod-borer, *H.armigera* (Hubn.), on chickpea (*Cicer arietinum* var. Shoba) in southern India. Crop Protection 19, 51-60.

Cherry, A.J., Banito, A., Djegui, D., Lomer, C., 2004. Suppression of the stem borer *Sesamia calamistis* (Lepidoptera: Noctuidae) in maize following seed dressing, topical application and stem injection with African isolates of *Beauveria bassiana*. International Journal of Pest Management 50, 67-73.

Choudhary, B., Gaur, K., 2010. Bt Cotton in India: A Country Profile. ISAAA Series of Biotech Crop Profiles. ISAAA: Ithaca, NY.

Christen, J.J., Campbell, J.F., Lewis, E.E., Shapiro-Ilan, D.I., Ramaswamy, S.B., 2007. Responses of the entomopathogenic nematode *Steinernema riobrave* to its insect hosts *Galleria mellonella* and *Tenebrio molitor*. Parasitology 134, 889-898.

Christian, P.D., Murray, D., Powell, R., Hopkinson, J., Gibb, N.N., Hanzlik,T.N., 2005. Effective control of a field population of *Helicoverpa armigera* by using the small RNA virus *Helicoverpa armigera* stunt virus (*Tetraviridae*: *Omegatetravirus*). Journal of Economic Entomology 98, 1839-1847.

Ciche, T.A., 2007. The biology and genome of *Heterorhabditis bacteriophora*. (February 20, 2007), WormBook, ed. The *C. elegans* Research Community, WormBook, doi/10.1895/wormbook.1.135.1, http://www.wormbook.org.

Ciche, T.A., Sternberg, P.W., 2007. Postembryonic RNAi in *Heterorhabditis bacteriophora*: a nematode insect parasite and host for insect pathogenic symbionts. BMC Developmental Biology 7, 101.

Cisneros, J., Angel-Perez, J., Penagos, D.I., Ruiz, V.J., Goulson, D., Caballero, P., Cave, R.D., Williams, T., 2002. Formulation of a nucleopolyhedrovirus with boric acid for control of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in maize. Biological Control 23, 87-95.

Clarke, D.J., 2008. *Photorhabdus*: a model for the analysis of pathogenicity and mutualism. Cell Microbiology 10, 2159–2167.

Cliquet, S., Jackson, M.A., 2005. Impact of carbon and nitrogen nutrition on the quality, yield and composition of blastospores of the bioinsecticidal fungus *Paecilomyces fumosoroseus*. Journal of Industrial Microbiology and Biotechnology 32, 204-210.

Cloyd, R.A., Zaborski, E.R., 2004. Fungus gnats, *Bradysia* spp. (Diptera: Sciaridae), and other arthropods in commercial bagged soilless growing media and rooted plant plugs. Journal of Economic Entomology 97, 503-510.

Coalition for GM free India (2012) 10 Years of Bt Cotton: False Hype and Failed Promises Cotton farmers' crisis continues with crop failure and suicides. http://www.keineentechnik.de/fileadmin/pics/Informationsdienst/SchulSeiten/fotos/2012_Coalition_GM_free_India_Bt_Cotton_Hype_False_Promises.pdf

Copping, L.G., 2009. Manual of Biocontrol Agents, 4th Edition. British Crop Protection Council, Alton, UK, p.1350.

Copping, L.G., Menn, J.J., 2000. Biopesticides: a review of their actions, applications and efficacy. Pest Management Science 56, 651-676.

Cory, J.S., Ericsson, J.D., 2010. Fungal entomopathogens in a tritrophic context. BioControl 55, 75-88.

Cory, J.S., Evans, H., 2007. Viruses. In: Lacey, L.A., Kaya, H.K. (Eds.), Field Manual of Techniques in Invertebrate Pathology: Application and Evaluation of Pathogens for Control of Insects and Other Invertebrate Pests, 2nd Edition. Springer, Dordrecht, The Netherlands, pp. 149-174.

Cory, J.S., Hoover, K., 2006. Plant mediated effects in insect-pathogen interactions. Trends in Ecology and Evolution 21, 278-286.

Cory, J.S., Myers, J.H., 2003. The ecology and evolution of insect baculoviruses. Annual Review of Ecology, Evolution and Systematics 34, 239-72.

Cottrell, T.E., Shapiro-Ilan, D.I., 2006. Susceptibility of the peachtree borer, *Synanthedon exitiosa*, to *Steinernema carpocapsae* and *Steinernema riobrave* in laboratory and field trials. Journal of Invertebrate Pathology 92, 85-88.

Couch, T. L., 2000. Industrial fermentation and formulation of entomopathogenic bacteria. In: Charles, J.-F., Delecluse, A., Nielsen-LeRoux, C. (Eds.), Entomopathogenic Bacteria: from laboratory to field application. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 297-316.

Couch, T.L., Ignoffo, C.M., 1981. Formulation of insect pathogens. In: Burges H.D. (Ed.), Microbial Control of Pests and Plant Diseases 1970-1980. London, Academic Press, pp. 621-634.

Cowles, C.E., Goodrich-Blair, H., 2008. The *Xenorhabdus nematophila nilABC* genes confer the ability of *Xenorhabdus* spp. to colonize *Steinernema carpocapsae* nematodes. Journal of Bacteriology 190, 4121-4128.

CPL Business Consultants. 2010. The 2010 Worldwide Biopesticides Market Summary Volume 1. CPL Scientific pp39..

Crickmore, N., Zeigler, D.R., Feitelson, J., Schnepf, E., Van Rie, J., Lereclus, D., Baum, J., Dean, D.H., 2014. *Bacilllus thuringiensis* toxin nomenclature, http://www.lifesci.sussex.ac.uk/Home/Neil_Crickmore/Bt/

Cross, J.V., Solomon, M.G., Chandler, D., Jarrett, P., Richardson, P.N., Winstanley, D., Bathon, H., Huber, J., Keller, B., Langenbruch, G.A., Zimmermann, G., 1999. Biocontrol of pests of apples and pears in Northern and Central Europe: 1. Microbial agents and nematodes. Biocontrol Science and Technology 9, 125-149.

Cross, J.V., Winstanley, D., Naish, N., Helton, S., Keane, G., van Wezel, R., Gakek, D., 2005. Semiochemical driven auto-dissemination of *Cydia pomonella* and *Adoxophyes orana* baculoviruses. IOBC Bulletin, 28, 319-324.

Cunningham, J. C., 1995. Baculoviruses as microbial pesticides. In: Reuveni, R. (Ed.), Novel Approaches to Integrated Pest Management. Lewis, Boca Raton, Florida, pp. 261–292.

Cuthbertson A. G. S., Walters K. F. A., 2005. Pathogenicity of the entomopathogenic fungus, *Lecanicillium muscarium*, against the sweetpotato whitefly *Bemisia tabaci* under laboratory and glasshouse conditions. *Mycopathologia*, 160, 315-319.

Cuthbertson, A.G.S., Walters, K.F.A., Northing, P., Luo, W., 2007. Efficacy of the entomopathogenic nematode, *Steinernema feltiae*, against sweetpotato whitefly *Bemisia tabaci* (Homoptera: Aleyrodidae) under laboratory and glasshouse conditions. Bulletin of Entomological Research 97, 9-14.

Da Silva, O.S., Prado, G.R., Da Silva, J.L.R., Silva, C.E., Da Costa, M., Heermann, R., 2013. Oral toxicity of *Photorhabdus luminescens* and X*enorhabdus nematophila* (Enterobacteriaceae) against *Aedes aegypti* (Diptera: Culicidae). Parasitology Research 112, 2891-2896.

Davidson, E.W. 2012. History of insect pathology. In: F. E. Vega and H. K. Kaya, (Eds). Insect Pathology, second ed. Academic Press, San Diego. pp. 13-28.

Davidson, M.M., Butler, R.C., Winkler, S., Teulon, D.A.J., 2007. Pyridine compounds increase trap capture of *Frankliniella occidentalis* (Pergande) in a covered crop. New Zealand Plant Protection 60, 56-60.

Davidson, M.M., Perry, N.B., Larsen, L., Green, V.C., Butler, R.C., Teulon, D.A.J., 2008. 4-pyridyl carbonyl compounds as thrips lures: effectiveness for western flower thrips in Y-tube bioassays. Journal of Agriculture and Food Chemistry 56, 6554-6561.

De Carvalho Barbosa Negrisoli, C.R., Negrisoli, A.S., Garcia, M.S., Dolinski, C., Bernardi, D., 2013. Control of *Grapholita molesta* (Busck, 1916) (Lepidoptera: Tortricidae) with entomopathogenic nematodes (Rhabditida: Heterorhabditidae, Steinernematidae) in peach orchards. Experimental Parasitology 135, 466-470.

de la Torre, M., 2003. Challenges for mass production of nematodes in submerged culture. Biotechnology Advances 21, 407-416.

de Morães Lessa, M., Medugno, C.C., 2001. Heteroflocculation of sulfate polystyrene latex and *Anticarsia gemmatalis* nucleopolyhedrovirus as a model system for studying sunlight protection. Journal of Colloid and Interface Science 239, 328-333.

Del Valle, E.E., Dolinksi, C., Barreto, E.L.S., Souza, R.M., Samuels, R.I., 2008. Efficacy of *Heterorhabditis baujardi* LP77 (Nematoda: Rhabditida) applied in *Galleria mellonella* (Lepidoptera: Pyralidae) insect cadavers to *Conotrachelus psidii* (Coleoptera: Curculionidae) larvae. Biocontrol Science and Technology 18, 33-41.

Del Valle, E.E., Dolinksi, C., Barreto, E.L.S., Souza, R.M., 2009. Effect of cadaver coatings on emergence and infectivity of the entomopathogenic nematode *Heterorhabditis baujardi* LPP7 (Rhabditida: Heterorhabditidae) and the removal of cadavers by ants. Biological Control 50, 21-24.

Dempsey, C.M., Griffin, C.T., 2002. Phased activity in *Heterorhabditis megidis* infective juveniles. Parasitology 124, 605-613.

Denno, R.F., Gruner, D.S., Kaplan, I., 2008. Potential for entomopathogenic nematodes in biological control: a meta-analytical synthesis and insights from trophic cascade theory. Journal of Nematology 40, 61-72.

Department of Biotechnology India, 2007. List of biopesticides and their producers. http://www.dbtbiopesticides.nic.in/upfiles/st_doc/Listofbiopesticidesandcommercialproducers.pdf. (accessed 20 January 2014)

Despres, L., Lagneau, C., Frutos, R., 2011. Using the bio-insecticide *Bacillus thuringiensis israelensis* in mosquito control. In: M. Stoytcheva (Ed.), Pesticides in the Modern World. http://www.intechopen.com/books/mostdownloaded/pesticides-in-the-modern-world-pests-control-and-pesticides-exposure-and-toxicity-assessment

Dillon, A.B., Downes, M.J., Ward, D., Griffin, C.T., 2007. Optimizing application of entomopathogenic nematodes to manage large pine weevil, *Hylobius abietis* L. (Coleoptera: Curculionidae) populations developing in pine stumps, *Pinus sylvestris.* Biological Control 40, 253-263.

Dillman, A.R., Guillermin, M.L., Lee, J., Kim, B., Sternberg, P.W., Hallem, E.A., 2012. Olfaction shapes host-parasite interactions in parasitic nematodes. Proceedings of the National Academy of Sciences of the United States of America 109(35), E2324-E2333.

Dimbi, S., Maniania, N.K., Lux, S.A., Ekesi S., Mueke, J.K., 2003. Pathogenicity of *Metarhizium anisopliae* (Metsch.) Sorokin and *Beauveria bassiana* (Balsamo) Vuillemin, to three adult fruit fly species: *Ceratitis capitata* (Weidemann), *C. rosai* var. *fasciventris* Karsch and *C. cosyra* (Walker) (Diptera: Tephritidae). Mycopathalogia 156, 375-382.

Dively, G.P., Rose, R., Sears, M.K., Hellmich, R.L., Stanley-Horn, D.E., Calvin, D.D., Russo, J.M., Anderson, P.L., 2004. Effects on monarch butterfly larvae (Lepidoptera: Danaidae) after continuous exposure to Cry1Ab—expressing corn during anthesis. Environmental Entomology 33, 1116–1125.

Dolci, P., Guglielmo, F., Secchi, F., Ozino, O., 2006. Persistence and efficacy of Beauveria brongniartii strains applied as biocontrol agents against Melolontha melolontha in the Valley of Aosta (northwest Italy).Journal of Applied Microbiology 100. 1063-1072.

Dolinski, C., Del Valle, E., Stuart, R.J., 2006. Virulence of entomopathogenic nematodes to larvae of the guava weevil, *Conotrachelus psidii* (Coleoptera: Curculionidae), in laboratory and greenhouse experiments. Biological Control 38, 422-427.

Douches, D.S., Li, W., Zarka, K., Coombs, J., Pett, W., Grafius, E., El-Nasr, T., 2002. Development of *Bt-cryV* insect resistant potato lines Spunta-G2 and Spunta-G3. HortScience 37, 1103-1107.

Douches, D.S., Coombs, J., Lacey, L.A., Felcher, K., Pett, W., 2011. Evaluations of transgenic potatoes for resistance to potato tuberworm in the laboratory and field. American Journal of Potato Research. American Journal of Potato Research 88: 91-95.

Dowd, P.F., Vega, F.E., 2003. Autodissemination of *Beauveria bassiana* by sap beetles (Coleoptera: Nitidulidae) to overwintering sites. Biocontrol Science and Technology 13, 65-75.

Dowds, B.C.A., Peters, A., 2002. Virulence mechanisms. In: Gaugler, R. (Ed.), Entomopathogenic Nematology. CABI, Wallingford, UK, pp. 79-98.

Down, R. E., Cuthbertson, A. G. S., Mathers, J. J., Walters, K. F. A., 2009. Dissemination of the entomopathogenic fungi, *Lecanicillium longisporum* and *L. muscarium*, by the predatory bug, *Orius laevigatus*, to provide concurrent control of *Myzus persicae, Frankliniella occidentalis* and *Bemisia tabaci*. Biological Control 50, 172-178.

Doyle, C.J., Entwistle, P.F., 1987. Aerial application of mixed virus formulations to control joint infestations of *Panolis flammea* and *Neodiprion sertifer* on lodgepole pine. Annals of Applied Biology 113, 119-127.

Dransfield, R.D., Brightwell, R., Kyorku, C., Williams, B., 1990. Control of tsetse fly (Diptera: Glossinidae) populations using traps at Nguruman, south-west Kenya. Bulletin of Entomological Research 80, 265-276.

Driver, F., Milner, R.J., Trueman, J.W.H., 2000. A taxonomic revision of *Metarhizium* based on phylogenetic analysis of rDNA sequence data. Mycological Research 104, 134-150.

Dromph, K.M., 2003. Collembolans as vectors of entomopathogenic fungi. Pedobiologia 47, 245-256.

Duchaud, E., Rusniok, C., Frangeul, L., Buchrieser, C., Givaudan, A., Taourit, S., Bocs., S., Boursaux-Eude, C., Chandler, M., Charles, J.F., Dassa, E., Derose, R., Derzelle, S., Freyssinet, G., Gaudriault, S., Medigue, C., Lanois, A., Powell, K., Siguier, P., Vincent, R., Wingate, V., Zouine, M., Glaser, P., Boemare, N., Danchin, A., Kunst, F., 2003. The genome sequence of the entomopathogenic bacterium *Photorhabdus luminescens*. Nature Biotechnology 21, 1307–1313.

Duncan, L.W, Dunn, D.C., Bague, G., Nguyen, K., 2003a. Competition between entomopathogenic and free-living bactivorous nematodes in larvae of the weevil *Diaprepes abbreviatus*. Journal of Nematology 35, 187-193.

Duncan, L.W, Graham, J.H., Dunn, D.C., Zellers, J., McCoy, C.W., Nguyen, K., 2003b. Incidence of endemic entomopathogenic nematodes following application of *Steinernema riobrave* for control of *Diaprepes abbreviatus*. Journal of Nematology 35, 178-186.

Duncan, L.W., Graham, J.H., Dunn, D.C., Zellers, J., Bright, D., Dunn, D.C., El-Borai, F.E., Porazinska, D.L., 2007. Food web responses to augmenting the entomopathogenic nematodes in bare and animal manure-mulched soil. Journal of Nematology 39, 176-189.

Duncan, L.W., Stuart, R.J., El-Borai, F.E., Campos-Herrera, R., Pathak, E., Giurcanu, M., Graham, J.H., 2013. Modifying orchard planting sites conserves entomopathogenic nematodes, reduces weevil herbivory and increases citrus tree growth, survival and fruit yield. Biological Control 64, 26-36.

Easom, C.A., Joyce, S.A., Clarke, D.J., 2010. Identification of genes involved in the mutualistic colonization of the nematode *Heterorhabditis bacteriophora* by the bacterium *Photorhabdus luminescens*. BMC Microbiology 10, 45.

Eberle, K.E., Jehle, J.A., 2006. Field resistance of codling moth against *Cydia pomonella* granulovirus (CpGV) is autosomal and incompletely dominant inherited. Journal of Invertebrate Pathology 93, 201-206.

Eberle, K.E., Asser-Kaiser, S., Sayed, S.M., Nguyen, H.T., Jehle, J.A., 2008. Overcoming the resistance of codling moth against conventional *Cydia pomonella* granulovirus (CpGV-M) by a new isolate CpGV-I12. Journal of Invertebrate Pathology 93, 293-298.

Eberle, K.E., Sayed, S., Rezapanah, M., Shojai-Estabragh, S., Jehle, J.A., 2009. Diversity and evolution of the *Cydia pomonella* granulovirus. Journal of General Virology 90, 662-671.

Eberle, K.E., Wennmann, J. T., Kleespies, R.G. Jehle, J.A., 2012. Basic techniques in insect virology. In: Lacey, L.A. (Ed.), Manual of Techniques in Invertebrate Pathology. Academic Press, San Diego. pp. 16-75.

Edwards, M. G., Poppy, G. M., 2009. Environmental impacts of genetically modified crops. In Ferry, N. and Gatehouse, A. (Eds) Environmental Impact of Genetically Modified Crops, CABI publishing, Wallingford. pp. 23-41.

Efron, D., Nestel, D., Glazer, I., 2001. Spatial analysis of entomopathogenic nematodes and insect hosts in a citrus grove in a semi-arid region in Israel. Environmental Entomology 30, 254-261.

Ehlers, R.-U., 2005. Forum on safety and regulation. In: Grewal, P.S., Ehlers, R.-U., Shapiro-Ilan, D.I. (Eds.), Nematodes as Biocontrol Agents. CABI, Wallingford, UK, pp. 107-114.

Ehlers, R.-U., 2007. REBECA Regulation of Biological Control Agents Final activity report SSPE-CT-2005 022709 http://www.rebeca-net.de/?p=320. (accessed 25 April 2010).

Ehlers R., (Ed.) 2011. Regulation of Biological Control Agents. Springer. Dordrecht. 416pp.

Ehlers, R.-U., Shapiro-Ilan, D.I., 2005. Mass production. In: Grewal, P.S., Ehlers, R.-U., Shapiro-Ilan, D.I. (Eds.), Nematodes as Biocontrol Agents. CABI Publishing, Wallingford, UK, pp. 65-78.

Ehlers, R.-U., Oestergaard, J., Hollmer, S., Wingen, M., Strauch, O., 2005. Genetic selection for heat tolerance and low temperature activity of the entomopathogenic nematode-bacterium complex *Heterorhabditis bacteriophora-Photorhabdus luminescens*. BioControl 50, 699-716.

Ekesi, S., Maniania, N.K. (Eds.), 2007. Use of Entomopathogenic Fungi in Biological Pest Management. Research Signpost, Kerala, India.

Ekesi, S., Dimbi, S., Maniania, N.K., 2007. The role of entomopathogenic fungi in the integrated management of fruit flies (Diptera: Tephritidae) with emphasis on species occurring in

Africa. In: Ekesi, S., Maniania, N.K. (Eds.), Use of Entomopathogenic Fungi in Biological Pest Management. Research Signpost, Kerala, India, pp. 239-274.

El-Borai, F.E., Bright, D.B., Graham, J.H., Stuart, R.J., Cubero, J., Duncan, L.W., 2009. Differential susceptibility of entomopathogenic nematodes to nematophagous fungi from Florida citrus orchards. Nematology 11, 231-241.

Elliot, S.L., Sabelis, M.W., Janssen, A., van der Geest, L.P.S., Beerling, E.A.M., Fransen, J., 2000. Can plants use entomopathogens as bodyguards? Ecology Letters 3, 228-235.

Ellis, J.D., Spiewok, S., Delaplane, K.S., Buchholz, S., Neumann, P., Tedders, W.L., 2010. Susceptibility of *Aethina tumida* (Coleoptera: Nitidulidae) larvae and pupae to entomopathogenic nematodes. Journal of Economic Entomology 103, 1126-1134.

Engler, K.M., Gold, R.E., 2004. Effects of multiple generations of *Metarhizium anisopliae* on subterranean termites feeding and mortality. Sociobiology 44, 211-240.

Enkerli, J., Widmer, F., 2010. Molecular ecology of fungal entomopathogens: molecular genetic tools and their applications in population and fate studies. BioControl 55, 17-37.

Enkerli, J., Widmer, F., Gessler, C., Keller, S., 2001. Strain-specific microsatellite markers in the entomopathogenic fungus *Beauveria brongniartii*. Mycological Research 105, 1079-1087.

Enkerli, J., Widmer, F., Keller, S., 2004. Long-term field persistence of *Beauveria brongniartii* strains applied as biocontrol agents against European cockchafer larvae in Switzerland. Biological Control 29, 115-123.

Enkerli, J., Kölliker, R., Keller, S., Widmer, R., 2005. Isolation and characterization of microsatellite markers from the entomopathogenic fungus *Metarhizium anisopliae*. Molecular Ecology Notes 5, 384-386.

Enkerli, J., Schwarzenbach, K., Widmer, F., 2008. Assessing potential effects of the *Beauveria brongniartii* biological control agent on fungal community structures in soil microcosms. In: Abstracts, 41st Annual Meeting of the Society for Invertebrate Pathology, Aug 3-8, 2008. Warwick University, UK, pp. 81.

Ennis, D.E., Dillon, A.B., Griffin, C.T., 2010. Simulated roots and host feeding enhance infection of subterranean insects by the entomopathogenic nematode *Steinernema carpocapsae*. Journal of Invertebrate Pathology 103, 140-143.

Entz, S.C., Johnson, D.L., Kawchuk, L.M., 2005. Development of a PCR-based diagnostic assay for specific detection of the entomopathogenic fungus *Metarhizium anisopliae* var. *acridum*. Mycological Research 109, 1302-1312.

European Commission, 2009. EU action on Pesticides Factsheet. Directorate-General for Health and Consumers, European Commission. ISBN 978-92-79-11599-8. http://ec.europa.eu/food/plant/plant_protection_products/eu_policy/docs/factsheet_pesticides_en.pdf (accessed 12 July 2014)

Fallon, D.J., Kaya, H.K., Gaugler, R., Sipes, B.S., 2002. Effects of entomopathogenic nematodes on *Meloidogyne javanica* on tomatoes and soybeans. Journal of Nematology 34, 239-245.

Fallon, D.J., Kaya, H.K., Gaugler, R., Sipes, B.S., 2004. Effect of *Steinernema feltiae-Xenorhabdus bovienii* insect pathogen complex on *Meloidogyne javanica*. Nematology 6, 671-680.

Faria, M.R., Wraight, S.P., 2007. Mycoinsecticides and mycoacaricides: a comprehensive list with worldwide coverage and international classification of formulation types. Biological Control 43, 237-256.

Farrar, R.R. Jr., Shapiro, M., Javaid, I., 2003. Photostabilized titanium dioxide and a fluorescent brightener as adjuvants for a nucleopolyhedrovirus. BioControl 48, 543-560.

Farrar, R.R. Jr., Shapiro, M., Shepard, B.M., 2005. Enhanced activity of the nucleopolyhedrovirus of the fall armyworm (Lepidoptera: Noctuidae) on Bt-transgenic and nontransgenic sweet corn with a fluorescent brightener and a feeding stimulant. Environmental Entomology 34, 825-832.

Farrar, R.R., Shapiro, M., Shepard, M., 2007. Relative activity of baculoviruses of the diamondback moth *Plutella xylostella* (L) (Lepidoptera: Plutellidae). BioControl 52, 657-667.

Farrar, R.R., Shepard, B.M., Shapiro, M., Hassell, R.L., Schaffer, M.L., Smith, C.M., 2009. Supplemental control of lepidopterous pests on Bt transgenic sweet corn with biologically based spray treatments. Journal of Insect Science 9, 8, available online insectscience.org/9.08.

Federici, B.A., 2005. Insecticidal bacteria: an overwhelming success for invertebrate pathology. Journal of Invertebrate Pathology 89, 30-38.

Federici, B.A., Park, H.-W., Bideshi, D.K., Wirth, M.C., Johnson, J.J., Sakano, Y., Tang, M., 2007. Developing recombinant bacteria for control of mosquito larvae. Bulletin of the American Mosquito Control Association 7, 164-175.

Fenton, A., Rands, S.A., 2004. Optimal parasite infection strategies: a state-dependant approach. International Journal of Parasitology 34, 813-821.

ffrench-Constant, R.H., Dowling, A., Waterfield, N.R., 2007. Insecticidal toxins from *Photorhabdus* bacteria and their potential use in agriculture. Toxicon 49, 436-451.

Fife, J.P., Derksen, R.C., Ozkan, H.E., Grewal, P.S., 2003. Effects of pressure differentials on the viability and infectivity of entomopathogenic nematodes. Biological Control 27, 65-72.

Fife, J.P., Derksen, R.C., Ozkan, H.E., Grewal, P.S., Chalmers, J.J., Krause, C.R., 2004. Evaluation of a contraction flow field on hydrodynamic damage to entomopathogenic nematodes-a biological pest control agent. Biotechnology and Bioengineering 86, 96-107.

Fife, J.P., Ozkan, H.E., Derksen, R.C., Grewal, P.S., 2006. Using computational fluid dynamics to predict damage of a biological pesticide during passage through a hydraulic nozzle. Biosystems Engineering 94, 387-396.

Food Standards Agency, 2013. Biannual public attitudes tracker November 2013. Social Science Research Unit, Food Standards Agency, London, pp. 62 (accessed 12 July 2014 http://food.gov.uk/science/research/ssres/publictrackingsurvey/)

Foster, W.A., Walker, E.D., 2009. Mosquitoes (Culicidae). In: Mullen, G.R., Durden, L.A. (Eds.), Medical and Veterinary Entomology, 2nd Edition. Academic Press, San Diego, CA, USA, pp. 201-253.

Fransen, J. J., 1990. Natural enemies of whiteflies: Fungi. In: Gerling, D. (Ed.), Whiteflies: their bionomics, Pest Status and Management. Intercept Andover, UK, pp. 187-210.

Franzmann, B.A., Hardy, A.T., Murray, D.A.H., Henzell, R.G., 2008. Host plant reistance and biopesticides: ingrediants for successful integrated pest management (IPM) in Australian Sorghum production. Australian Journal of Experimental Agriculture 48, 1594-1600.

Freimoser, F.M., Hu, G., St. Leger, R.J., 2005. Variation in gene expression patterns as the insect pathogen *Metarhizium anisopliae* adapts to different host cuticles or nutrient deprivation *in vitro*. Microbiology 151, 361-371.

Fritsch, E.K., Undorf-Spahn, J., Kienzle, C.P., Zebitz,W., Huber, J., 2005. Apfelwickler granulovirus: erste hinweise auf unterschiede in der empfindlichkeit lokaler apfelwickler populationen. Nachrichtenbl. Dtsch. Pflanzenschutzd 57, 29-34.

Fujimoto, A., Lewis, E.E., Cobanoglu, G., Kaya, H.K., 2007. Dispersal, infectivity and sex ratio of early- or late-emerging infective juveniles of the entomopathogenic nematode *Steinernema carpocapsae*. Journal of Nematology 39, 333-337.

Furlong M.J. Wright D.J. and Dodsall L.M. (2013) Diamondback moth ecology and management: problems, progress and prospects. Annual Review of Entomology, 58, 517-41.

Fushing, H.L., Zhu, L., Shapiro-Ilan, D.I., Campbell, J.F., Lewis, E.E., 2009. State-space based mass event-history model I: many decision-making agents with one target. Annals of Applied Statistics. 2, 1503-1522.

Fuxa, J.R., 2004. Ecology of nucleopolyhedroviruses. Agriculture Ecosystems and Environment 103, 27-43.

Fuxa, J.R., Aaappath, R., Goyer, R.A., 1998. Pathogens and microbial control of North American forest insect pests. USDA Forest Service FHTET-97-27.

Galitsky, N., Cody, V., Wojtczak, A., Ghosh, D., Luft, J.R., Pangborn, W., English, L., 2001. Structure of the insecticidal bacterial δ-endotoxin CryBb1 of *Bacillus thuringiensis*. *Acta Crystallographica* D57, 1101–1109.

Gan-Mor, S., Matthews, G.A., 2003. Recent developments in sprayers for application of biopesticides- an overview. Biosystems Engeneering 84, 119-125.

Gassmann, A.L., Stock, S.P., Sisterson, M.S., Carrière, Y., Tabashnik, B.E., 2008. Synergism between entomopathogenic nematodes and *Bacillus thuringiensis* crops: integrating biological control and resistance management. Journal of Applied Ecology 45, 957-966.

Gaugler, R., 1987. Entomogenous nematodes and their prospects for genetic improvement. In: Maramorosch, K. (Ed.), Biotechnology in Invertebrate Pathology and Cell Culture. Academic Press, San Diego, CA, pp. 457-484.

Gaugler, R. (Ed.), 2002. Entomopathogenic Nematology. CABI Publishing, Wallingford, UK, 388 pp.

Gaugler, R., Han, R., 2002. Production technology. In: Gaugler, R. (Ed.), Entomopathogenic Nematology. CABI, Wallingford, UK, pp 289-310.

Gaugler, R., Brown, I., Shapiro-Ilan, D.I., Atwa, A., 2002. Automated technology for *in vivo* mass production of entomopathogenic nematodes. Biological Control 24, 199-206.

Gelernter, W.D., 2002. The discovery, development and death of *Bacillus thuringiensis* as a microbial control product for the Colorado potato beetle. In: Proceedings of VIII International Colloquium on Invertebrate Pathology and Microbial Control, Foz de Iguaçu, Brazil, August 18-23, 2002, Society for Invertebrate Pathology, published in Documentos Embrapa Soja 184, 262-264.

Gelernter, W.D., Trumble, J.T., 1999. Factors in the success and failure of microbial insecticides in vegetable crops. Integrated Pest Management Reviews 4, 301-306.

Genissel, A., Leple, J.C., Millet, N., Augustin, S., Jouanin, L., Pilate, G., 2003. High tolerance against *Chrysomela tremulae* of transgenic Poplar plants expressing a synthetic cry3Aa gene from *Bacillus thuringiensis* ssp. *tenebrionis*. Molecular Breeding 11, 103-110.

Georgis, R., 2002. The Biosys experiment: an insider's perspective. In: Gaugler, R., (Ed.), Entomopathogenic Nematology. CABI, Wallingford, UK, pp 357-372.

Georgis, R., Koppenhöfer, A.M., Lacey, L.A., Bélair, G., Duncan, L.W., Grewal, P.S., Samish, M., Tan, L., Torr P., van Tol, R.W.H.M., 2006. Successes and failures in the use of parasitic nematodes for pest control. Biological Control 38, 103-123.

Gil, G.H., Choo, H.Y., Gaugler, R., 2002. Enhancement of entomopathogenic nematode production in in-vitro liquid culture of *Heterorhabditis bacteriophora* by fed-batch culture with glucose supplementation. Applied Microbiology and Biotechnology 58, 751-755.

Girard, F., Vachon, V., Prefontaine, G., Marceau, L., Schwartz, J.L., Masson, L., Laprade, R., 2009. Helix alpha 4 of the *Bacillus thuringiensis* Cry1Aa toxin plays a critical role in the postbinding steps of pore formation. Applied and Environmental Microbiology 75, 359-365.

Glare, T.R, O'Callaghan, M., 2000. *Bacillus thuringiensis*: Biology, Ecology and Safety. J. Wiley and Sons, Ltd., Chichester, UK, 350 pp.

Glare, T.R., Caradus, J., Gelernter, W., Jackson,T., Keyhani,N., Kohl, J., Marrone, P., Morin, L., Stewart, A., 2012. Have biopesticides come of age? Trends in Biotechnology 30, 250-258.

Glare, T.R., Goettel, M.S., Eilenberg, J., 2010. Addendum: entomopathogenic fungi and their role in regulation of insect populations, 2004-2009, in: Gilbert, L.I., Gill, D.S. (Eds.), Insect Control: Biological and Synthetic Agents, Academic Press, San Diego, pp 432-438.

Goettel, M.S., Eilenberg, J., Glare, T.R., 2005. Entomopathogenic fiungi and their role in regulation of insect populations. In: Gilbert, L.I., Iatrou, K., Gill, S. (Eds.), Comprehensive Molecular Insect Science, Vol. 6. Elsevier, pp 361-406.

Goettel, M.S., Eilenberg, J., Glare, T.R., 2010. Entomopathogenic fungi and their role in regulation of insect populations, in: Gilbert, L.I., Gill, D.S. (Eds.), Insect Control: Biological and Synthetic Agents, Academic Press, San Diego pp 387-431.

Goettel, M.S., Hajek, A.E., Siegel, J.P., Evans, H.C., 2001. Safety of Fungal Biocontrol Agents. In: Butt, T., Jackson, C., Magan, N. (Eds.), Fungi as Biocontrol Agents-Progress, Problems and Potential. CABI Press, Wallingford, UK, pp 347-375.

Goettel, M.S., Koike, M., Kim, J.J. Aiuchi, D., Shinya, R., Brodeur, J., 2008. Potential of *Lecanicillium* spp. for management of insects, nematodes and plant diseases. Journal of Invertebrate Pathology 98, 256-261.

Gómez-Bonilla, Y., M. López-Ferber, M., P. Caballero P., Léry X., D. Muñoz, D. 2011. Characterization of a Costa Rican granulovirus strain highly pathogenic against its indigenous hosts, *Phthorimaea operculella* and *Tecia solanivora*. Entomologia Experimentalis et Applicata 140, 238–246.

Goodrich-Blair, H., 2007. They've got a ticket to ride: *Xenorhabdus nematophila-Steinernema carpocapsae* symbiosis. Current Opinion in Microbiology 10, 225-230.

Goulson, D., 2003. Can host susceptibility to Baculovirus infection be predicted from host taxonomy or life history? Environmental Entomology 32, 61-70.

Graham, R.I., Grzywacz, D., Mushobozi, W., Wilson, K., 2010. *Wolbachia* in a major African crop pest increases susceptibility to viral disease rather than protects. Ecology Letters 15, 993-1000.

Granados, R.R., Li, G., Blissard, G.W., 2007. Insect cell culture and biotechnology. Virologica Sinica 22, 83-93.

Grewal, P.S., Power, K.T., Grewal, S.K., Suggars, A., Haupricht, S., 2004. Enhanced consistency of white grubs (Coleoptera: Scarabaeidae) with new strains of entomopathogenic nematodes. Biological Control 30, 73-82.

Grewal, P.S., Ehlers, R.-U., Shapiro-Ilan, D.I. (Eds.), 2005a. Nematodes as Biocontrol Agents. CABI, Wallingford, UK. 505 pp.

Grewal, P.S., Ehlers, R.-U., Shapiro-Ilan, D.I., 2005b. Critical issues and research needs for expanding the use of nematodes in biocontrol. In: Grewal, P.S., Ehlers, R.-U., Shapiro-Ilan, D.I. (Eds.), Nematodes as Biological Control Agents. CABI, Wallingford, UK, pp. 479-489.

Griffitts, J.S., Aroian, R.V., 2005. Many roads to resistance: how invertebrates adapt to Bt toxins. Bioessays 27, 614-624.

Grochulski, P., Masson, L., Borisova, S., Pusztai-Carey, M., Schwartz, J.L., Brousseau, R., Cygler, M., 1995. *Bacillus thuringiensis* CryIA(a) insecticidal toxin: crystal structure and channel formation. Journal of Molecular Biology 254, 447–464.

Gross, M., 2013. EU ban puts spotlight on complex effects of neonicotinoids. Current Biology 23, R462-R464.

Gruere, G.P., Mehta-Bhatt, P., Sengupta, D. 2008. Bt cotton and farmer suicides: reviewing the evidence. International Food Policy Research Institute, Discussion paper 00808, IFPRI, Rome.

Grzywacz, D., Cherry, A. C., Gwynn R. 2009. Biological pesticides for Africa: why has so little of the research undertaken to date led to new products to help Africa's poor? Pesticide. Outlook, 20, 77-81.

Grzywacz, D., Parnell, D., Kibata, G., Odour, G., Ogutu, O. O., Miano, D., Winstanley, D., 2004. The development of endemic baculoviruses of *Plutella xylostella* (Diamondback moth, DBM) for control of DBM in East Africa. In: Endersby, N., Ridland, P.M. (Eds.), The Management of Diamondback Moth and Other Crucifer Pests. Proceedings of the 4th International Workshop, 26-29 Nov 2001. Melbourne, Victoria, Australia, pp. 197-206.

Grzywacz, D., Richards, A., Rabindra, R.J., Saxena, H., Rupela, O.P., 2005. Efficacy of biopesticides and natural plant products for Heliothis/*Helicoverpa* control. In: Sharma, H.C.

(Ed.), Heliothis/Helicoverpa Management–Emerging Trends and Strategies for Future Research. Oxford and IBH Pub.Co. Pvt. Ltd., New Delhi, India, pp. 371-389.

Grzywacz, D., Mushobozi, W.L., Parnell, M., Jolliffe, F., Wilson, K., 2008. The evaluation of *Spodoptera exempta* nucleopolyhedrovirus (SpexNPV) for the field control of African armyworm (*Spodoptera exempta*) in Tanzania. Crop Protection 27, 17-24.

Grzywacz, D., Moore, D. and Rabindra R.J. 2014a. Mass Production of Entomopathogens in Less Industrialized Countries. In: Juan A. Morales-Ramos, M. Guadalupe Rojas, and David, I. Shapiro-Ilan (Eds.) Mass Production of Beneficial Organisms, Elsevier, Amsterdam.pp 519-553.

Grzywacz, D., Stevenson P.C., Mushobozi, W.M., Belmain, S., Wilson. K. 2014b. The use of indigenous ecological resources for pest control in Africa. Food Security (in press).DOI 10.1007/s12571-013-0313-5

Gywnn, R. (Ed.) 2014 Manual of biocontrol agents 5th edition, British Crop Protection Council, Alton. (In press).

Hajek, A.E., 1997. Ecology of terrestrial fungal entomopathogens. Advances in Microbial Ecology 15, 193-249.

Hajek, A.E., 2007. Introduction of a fungus into North America for control of gypsy moth. In: Vincent, C., Goettel, M.S., Lazarovits, G. (Eds.), Biological control: A global perspective. CAB International, Wallingford, UK, pp. 53-62.

Hajek, A.E., 2009. Invasive arthropods and approaches to their microbial control. In: Hajek, A.E., Glare, T.R., O'Callaghan, M. (Eds.), Use of Arthropods for Control and Eradication of Invasive Arthropods. Springer BV, Netherlands, pp. 3-18.

Hajek, A.E., St. Leger, R., 1994. Interactions between fungal pathogens and insect hosts. Annual Review of Entomology 39, 293-322.

Hajek, A.E., Delalibera, L. Jr., 2010. Fungal pathogens as classical biological control agents against arthropods. BioControl 55, 147–158.

Hajek, A.E. and M.S. Goettel, 2007. Guidelines for evaluating effects of entomopathogens on non-target organisms. In: Lacey, L.A., Kaya, H.K. (Eds.), Field Manual of Techniques in Invertebrate Pathology: Application and Evaluation of Pathogens for Control of Insects and Other Invertebrate Pests, 2nd Edition. Springer, Dordrecht, The Netherlands,pp 815 – 833.

Hajek, A.E., Delalibera, I. Jr., McManis, L., 2007. Introduction of exotic pathogens and documentation of their establishment and impact. In: Lacey, L.A., Kaya, H.K. (Eds.), Field Manual of Techniques in Invertebrate Pathology: Application and Evaluation of Pathogens for Control of Insects and Other Invertebrate Pests, 2nd Edition. Springer, Dordrecht, The Netherlands, pp. 299-325.

Hajek, A.E., Glare, T.R., O'Callaghan, M., (Eds.), 2009. Use of Microbes for Control and Eradication of Invasive Arthropods. Springer, Dordrecht, The Netherlands, 366 pp.

Hajek, A. E., Papierok, B., Eilenberg, J., 2012. Methods for study of the Entomophthorales. In: Lacey, L.A. (Ed.), Manual of Techniques in Invertebrate Pathology. Academic Press, San Diego. pp. 285-316.

Han, R., Ehlers, R.-U., 2001. Effect of *Photorhabdus luminescens* phase variants on the in vivo and in vitro development and reproduction of the entomopathogenic nematodes *Heterorhabditis bacteriophora* and *Steinernema carpocapsae*. FEMS Microbiology Ecology 35, 239-247.

Hao, Y.-J., Montiel, R., Nascimento, G., Toubarro, D., Simões, N., 2008. Identification, characterization of functional candidate genes for host-parasite interactions in entomopathogenic nematode *Steinernema carpocapsae* by suppressive subtractive hybridization. Parasitology Research 103, 671-683.

Hao, Y-J., Montiel, R., Lucena, M.A., Costa, M., Simões, N., 2012. Genetic diversity and comparative analysis of gene expression between *Heterorhabditis bacteriophora* Az29 and Az36 isolates: Uncovering candidate genes involved in insect pathogenicity. Experimental Parasitology 130, 116–125.

Harrison, R., Hoover, K., 2012. Baculoviruses and other occluded insect viruses. In: Vega, F., Kaya, H. (Eds.), Insect Pathology, Elsevier, Amsterdam, pp. 73–131.

Hartmann, M., Frey, B., Kölliker, R., Widmer, F., 2005. Semi-automated genetic analyses of soil microbial communities: comparison of T-RFLP and RISA based on descriptive and discriminative statistical approaches. Journal of Microbiological Methods 61, 349-360.

Hauxwell, C., Reeson, A., 2008. Improved formulations of baculovirus insecticides against *Helicoverpa armigera* in Australian broad acre crops. Proceedings XXIII International Congress of Entomology 6-12 July, 2008, Durban, South Africa, pp.1104.

Hauxwell, C., Tichon, M., Buerger, P., Anderson, S. 2010. Australia. In: Kabaluk, J.T., Svircev,A.M., Goettel, M.S., Woo, S.G. (Eds.), The Use and Regulation of Microbial Pesticides in Representative Jurisdictions Worldwide, IOBC Global, pp. 80–88.

Head, G. P., Greenplate, J., 2012. The design and implementation of insect resistance management programs for Bt crops. GM Crops Food. 3, 144-153.

Hellmich, R.L., Siegfried, B.D., Sears, M.K., Stanley-Horn, D.E., Daniels, M.J., Mattila, H.R., Spencer, T., Bidne, K.G., Lewis, L.C., 2001. Monarch larvae sensitivity to *Bacillus* *thuringiensis*—purified proteins and pollen. Proceedings of the National Academy of Sciences USA 98, 11925–11930.

Herniou, E.A., Arif, B.M., Becnel, J.J., Blissard, G.W., Bonning, B., Harrison, R., Jehle, J.A.,Theilmann,D.A., Vlak, J.M., 2012. Family Baculoviridae. In: King, A.M.Q., Adams, M.J.,Carstens, E.B., Lefkowitz, E.J. (Eds.), Virus Taxonomy, Classification and Nomenclature of Viruses, Ninth Report of the International Committee on Taxonomy of Viruses, ElsevierAcademic Press, Amsterdam, pp. 163–173.

Hibbett, D.S., Binder, M., Bischoff, J.F., Blackwell, M., et al., 2007. A higher level phylogenetic classification of the fungi. Mycological Research 111, 509-547.

Hillocks, R., 2012. Farming with fewer pesticides; EU Pesticides review and resulting challenges for UK Agriculture. Crop Protection 31, 85-93.

Hiltpold, I., Hibbard, B.E., French, B.W., Turlings, T.C.J., 2012. Capsules containing entomopathogenic nematodes as a Trojan horse approach to control the western corn rootworm. Plant and Soil 358, 11-25.

Hirao, A., Ehlers, R.-U., 2010. Influence of inoculum density on population dynamics and dauer juvenile yields in liquid culture of biocontrol nematodes *Steinernema carpocapsae* and *S. feltiae* (Nematoda: Rhabditida). Applied Microbiology and Biotechnology 85, 507-515.

Hirao, A., Ehlers, R.-U., Strauch, O., 2010. Life cycle and population development of the entomopathogenic nematodes *Steinernema carpocapsae* and *S. feltiae* (Nematoda, Rhabditida) in monoxenic liquid culture. Nematology 12, 201-210.

Hodson, A.K., Siegel, J.P., Lewis, E.E., 2012. Ecological influence of the entomopathogenic nematode, *Steinernema carpocapsae*, on pistachio orchard soil arthropods. Pedobiologia 55, 51– 58.

Hokkanen, H.M.T., Hajek, A.E., (Eds.), 2003. Environmental Impacts of Microbial Insecticides: need and methods for risk assessment. Kluwer Academic Publishers, Dordrecht, The Netherlands, 269 pp.

Hoover, K., Stout, M.J., Alaniz, S.A., Hammock, B.D., Duffey, S.S., 1998. Influence of induced plant defences in cotton and tomato on the efficacy of baculoviruses on noctuid larvae. Journal of Chemical Ecology 24, 253-271.

Hoover, K., Washburn J.O., Volkman, L.E., 2000. Midgut-based resistance of *Heliothis virescens* to baculovirus infection mediated by phytochemicals in cotton. Journal of Insect Physiology 6, 999-1007.

Hoy, M. A., 2008a. Augmentative biological control. In: Capinera, J. L. (Ed.), Encyclopedia of Entomology 2nd ed. SpringerDordrecht, The Netherlands, pp. 327-334.

Hoy, M. A., 2008b. Classical biological control. In: Capinera, J. L. (Ed.), Encyclopedia of Entomology 2nd ed. SpringerDordrecht, The Netherlands, pp. 905-923.

Hoy, C.W., Grewal, P.S., Lawrence, J., Jagdale, G., Acosta, N., 2008. Canonical correspondence analysis demonstrates unique soil conditions for entomopathogenic nematode species compared with other free-living nematode species. Biological Control 46, 371-379.

Hu, G., St. Leger, R., 2002. Field studies using a recombinant mycoinsecticide (*Metarhizium anisopliae*) reveal that it is rhizosphere competent. Applied and Environmental Microbiology 68, 6383-6387.

Huanga, J., Hu, R., Pray, C., Qiao, F., Rozell, S., 2003. Biotechnology as an alternative to chemical pesticides: a case study of Bt cotton in China. Agricultural Economics 29, 55–67.

Huger, A.M., 2005. The *Oryctes* virus: its detection, identification, and implementation in biological control of the coconut palm rhinoceros beetle, *Oryctes rhinoceros* (Coleoptera: Scarabaeidae). Journal of Invertebrate Pathology 89, 78-84.

Hummel, R.L., Walgenbach, J.F., Barbercheck, M.E., Kennedy, G.G., Hoyt, G.D., Arellano. C., 2002. Effects of production practices on soil-borne entomopathogens in western North Carolina vegetable systems. Environmental Entomology 31, 84-91.

Hunter-Fujita, F.R., Entwistle, P.F., Evans, H.F., Crook, N.E. (Eds.), 1998. Insect Viruses and Pest Management. Wiley and Sons, New York, 632 pp.

Hussa, E.A., Goodrich-Blair, H., 2013. It takes a village: Ecological and fitness impacts of multipartite mutualism. Annual Review of Microbiology 67, 161-178.

Hyde, K.D., Soytong, K., 2008. The fungal endophyte dilemma. Fungal Diversity 33, 163-173.

Inceoglu, A.B., Kamita, S., Hammock, B.D., 2006. Genetically modified baculoviruses: historical overview and future outlook. In: Bonning, B.C. (Ed.), Advances in Virus Research, Volume 68, Insect Viruses: Biotechnological Applications. Academic Press, San Diego, pp. 109-126.

Ignoffo, C.M., 1992. Environmental factors affecting persistence of entomopathogens. Florida Entomologist 75, 516–525.

Ignoffo, C.M., 1999. The first viral pesticide: past present and future. Journal Industrial Microbiology and Biotechnology 22, 407-417.

Ilan, T., Kim-Shapiro, D.B., Bock, C.H., Shapiro-Ilan, D.I., 2013. The impact of magnetic fields, electric fields and current on the directional movement of *Steinernema carpocapsae*. International Journal of Parasitology, 43, 781-784.

Inglis, G.D., Johnson, D.L., Goettel, M.S., 1997. Use of pathogen combinations to overcome the constraints of temperature on entomopathogenic Hyphomycetes against grasshoppers. Biological Control 8, 143-152.

Inglis, G.D., Goettel, M.S., Butt, T.M., Strasser, H., 2001. Use of hyphomycetous fungi for managing insect pests. In: Butt, T., Jackson, C., Magan, N. (Eds.), Fungi as Biocontrol Agents-Progress, Problems and Potential. CABI Press, Wallingford, UK. CAB International, UK, pp. 23-69.

Inglis, G.D., Duke, G.M., Goettel, M.S., Kabaluk, J.T., 2008. Genetic diversity of *Metarhizium anisopliae* var. *anisopliae* in southwestern British Columbia. Journal of Invertebrate Pathology 98, 101-113.

Inglis, G.D., Enkerli, J., Goettel, M.S., 2012. Laboratory techniques used for entomopathogenic fungi: Hypocreales. In: Lacey, L.A. (Ed.), Manual of Techniques in Invertebrate Pathology. Academic Press, San Diego, pp. 189-253.

Inyang, E., Butt, T.M., Ibrahim, L., Clarke, S.J., Pye, B.J., Beckett, A., Archer, S., 1998. The effect of plant growth and topography on the acquisition of conidia of the insect pathogen *Metarhizium anisopliae* by larvae of *Phaedon cochleariae*. Mycological Research 102, 1365-

Isaacson, P.J., Webster, J.M., 2002. Antimicrobial activity of *Xenorhabdus* sp. RIO (Enterobacteriaceae) symbiont of the entomopathogenic nematode, *Steinernema riobrave* (Rhabditida: Steinernematidae). Journal of Invertebrate Pathology 79, 146-153.

Islas-López, M.-A., Sanjuan-Galindo, R., Rodriguez-Hernandez, A.-I., Chavarria-Hernandez, N., 2005. Monoxenic production of the entomopathogenic nematode *Steinernema carpocapsae* using culture media containing agave juice (aguamiel) from Mexican maguey-pulquero

(*Agave* spp.) effects of the contents of nitrogen, carbohydrates and fat on infective juvenile production. Applied Microbiology and Biotechnology 68, 91-97.

Jaber, L.R., Salem, N.M., 2014. Endophytic colonization of squash by the fungal entomopathogen *Beauveria bassiana* (Ascomycota: Hypocreales) for managing *Zucchini yellow mosaic virus* in curcurbits. Biocontrol Science and Technology 24, 1096-1109.

Jabbour, R., Barbercheck, M.E., 2008. Soil and habitat complexity effects on movement of the entomopathogenic nematode *Steinernema carpocapsae* in maize. Biological Control 47, 235-243.

Jackson, M.A., Cliquet, S., Iten, L.B., 2003. Media and fermentation processes for the rapid production of high concentrations of stable blastospores of the bioinsecticidal fungus *Paecilomyces fumosoroseus*. Biocontrol Science and Technology 13, 23-33.

Jackson, M.A., Erhan, S., Poprawski, T.J., 2006. Influence of formulation additives on the desiccation tolerance and storage stability of blastospores of the entomopathogenic fungus *Paecilomyces fumosoroseus* (Deuteromycotina: Hyphomycetes). Biocontrol Science and Technology 16, 61-75.

Jackson, M.A., Dunlap. C.A., Jaronski, S.T., 2010. Ecological considerations in producing and formulating fungal entomopathogens for use in insect biocontrol. BioControl 55, 129-145.

Jackson, T.A., 1999. Factors in the success and failure of microbial control agents for soil-dwelling pests. Integrated Pest Management Reviews, 281-285.

Jackson, T.A., 2003. Environmental safety of inundative application of a naturally occurring biocontrol agent, *Serratia entomophila*. In: Hokkanen, H.M.T., Hajek, A.E. (Eds.), Environmental Impacts of Microbial Insecticides: Need and mMethods for Risk Assessment. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp.169-176.

Jackson, T.A., 2007. A novel bacterium for control of grass grub. In: Vincent, C., Goettel, M.S., Lazarovits, G. (Eds.), Biological Control: A Global Perspective. CABI Publishing, Wallingford, U.K., pp 160-168.

Jackson, T. A. 2009 The Use of Oryctes Virus for control of rhinoceros beetle in the Pacific Islands. Use of Microbes for Control and Eradication of Invasive Arthropods Progress in Biological Control Volume 6, 2009, Springer, New York. pp 133-140

Jackson, T.A., Klein, M., 2006. Scarabs as pests: a continuing problem. In: Jameson, M.L., Ratcliffe, B.C. (Eds.), Scarabaeoidea in the 21st Century: a Festschrift honoring Henry F. Howde. Coleopterists Society Monograph Number 5, pp. 102-119.

Jackson, T. A., Pearson, J. F., O'Callaghan, M., Mahanty, H. K., Wilcocks, M. J., 1992. Pathogen to product – development of *Serratia entomophila* (Enterobacteriacea) as a commercial biological agent for the New Zealand grass grub (*Costelytra zealandica*). In: Jackson, T. A., and Glare, T. R., (Eds.) Use of Pathogens in Scarab Pest Management. 191-198. Intercept Press, Andover. pp. 191-198.

Jackson, T.A., Boucias, D.G., Thaler, J.O., 2001. Pathobiology of amber disease caused by *Serratia* spp., in the New Zealand grass grub, *Costelytra zealandica*. Journal of Invertebrate Pathology 78, 232-243.

Jackson, T.A., Crawford, A.M., Glare, T.R., 2005. *Oryctes* virus- time for a new look at a useful biocontrol agent. Journal of Invertebrate Pathology 89, 91-94.

Jagdale, G.B., Grewal, P.S., 2008. Influence of the entomopathogenic nematode *Steinernema carpocapsae* infected host cadaver or their extracts on the foliar nematode *Aphelenchoides fragariae* on *Hosta* in the greenhouse and laboratory. Biological Control 44, 13-23.

Jagdale, G.B., Somasekhar, N., Grewal, P.S., Klein, M.G., 2002. Suppression of plant-parasitic nematodes by application of live and dead infective juveniles of an entomopathogenic nematode, *Steinernema carpocapsae*, on boxwood (*Buxus* spp.). Biological Control 24, 42-49.

Jagdale, G.B., Casey, M.L., Grewal, P.S., Lindquist, R.K., 2004. Application rate and timing, potting medium, and host plant effects on efficacy of *Steinernema feltiae* against the fungus gnat, *Bradysia coprophila*, in floriculture. Biological Control 29, 296-305.

Jagdale, G.B., Casey, M.L., Canas, L., Grewal, P.S., 2007. Effect of entomopathogenic nematode species, split application and potting medium on the control of the fungus gnat, *Bradysia difformis* (Diptera: Sciaridae), in the greenhouse at alternating cold and warm temperatures. Biological Control 43, 23-30.

Jagdale, G.B., Kamoun, S., Grewal, P.S., 2009. Entomopathogenic nematodes induce components of systemic resistance in plants: biochemical and molecular evidence. Biological Control 51, 102-109.

James, C., 2013. Global Status of Commercialized Biotech/GM Crops: 2013. ISAAA Brief No. 44, Ithaca, NY.

James, R.R., 2009. Microbial control for invasive arthropod pests of honey bees. In: Hajek, A.E., Glare, T.R., O'Callaghan, M. (Eds.), Use of Arthropods for Control and Eradication of Invasive Arthropods. Springer BV, Netherlands, pp. 271-290.

Jaramillo, J., Borgemeister, C., Ebbsa, L., Gaigl, A., Tobón, R., Zimmermann, G., 2005. Effect of combined applications of *Metarhizium anisopliae* (Metsch.) Sorokin (Deuteromycotina: Hyphomycetes) strain CIAT 224 and different dosages of imidacloprid on the subterranean burrower bug *Cyrtomenus bergi* Froeschner (Hemiptera: Cydnidae). Biological Control 34, 12-20.

Jaronski, S.T., 2007. Soil ecology of the entomopathogenic Ascomycetes: A critical examination of what we (think) we know. In: Ekesi, S., Maniania, N.K. (Eds.), Use of Entomopathogenic Fungi in Biological Pest Management. Research Signpost, Kerala, India, pp 91-143.

Jaronski, S.T., 2010. Ecological factors in the inundative use of fungal entomopathogens. BioControl 55, 159-185.

Jaronski, S.T., Jackson, M.A., 2008. Efficacy of *Metarhizium anisopliae* microsclerotial granules. Biocontrol Science and Technology 18, 849-863.Jaronski, S.T., Jackson, M.A., 2012. Mass production of entomopathogenic Hypocreales. In: Lacey, L.A. (Ed.), Manual of Techniques in Invertebrate Pathology. Academic Press, San Diego, pp. 257-286.

Jehle, J. A., Blissard, G.W., Bonning, B.C, Cory, J.S., Herniou, E.A., Rohrmann, G.R., Theilmann, D.A., Theim, S.M., Vlak, J.M., 2006. On the classification and nomenclature of baculoviruses: a proposal for revision. Archives of Virology 151, 1257-66.

Jenkins, D.A., Shapiro-Ilan, D.I., Goenaga, R., 2008. Efficacy of entomopathogenic nematodes versus *Diaprepes abbreviatus* (Coleoptera: Curculionidae) larvae in a high clay content Oxisol soil: greenhouse trials with potted *Litchi chinensis*. Florida Entomologist 91, 75-78.

Jenkins, N.E., Gryzwacz, D., 2000. Quality control of fungal and viral biocontrol agents: assurance of product performance. Biocontrol Science and Technology 10, 753-777.

Ji, D., Yi, Y., Kang, G.-H., Choi, Y.-H., Kim, P., Baek, N.-I., Kim, Y., 2004. Identification of an antibacterial compound, benzylideneacetone, from *Xenorhabdus nematophila* against major plant-pathogenic bacteria. FEMS Microbiology Letters 239, 241-248.

Jiang, H., Zhou, L., Zhang, J.M., Dong, H.F., Hu, Y.Y., Jiang, M.S., 2008. Potential of *Periplanta fuliginosa* densovirus as a biocontrol agent for smoky-brown cockroach, *P.fuliginosa*. Biological Control 46, 94-100.

Johnigk, S.-A., Ecke, F., Poehling, M., Ehlers, R.-U., 2004. Liquid culture mass production of biocontrol nematodes, *Heterorhabditis bacteriophora* (Nematoda: Rhabditida): improved timing of dauer juvenile inoculation. Applied Microbiology and Biotechnology 64, 651-658.

Johnson, V.W., Pearson, J.F., Jackson, T.A., 2001. Formulation of *Serratia entomophila* for biological control of grass grub. New Zealand Plant Protection 54, 125-127.

Jones, K.A., Irving, N.S., Moawad, G., Grzywacz, D., Hamid, A., Farghaly, A., 1994. Field trials with NPV to control *Spodoptera littoralis* on cotton in Egypt. Crop Protection 13, 337-340.

Jung, S., Kim, Y., 2006. Synergistic effect of *Xenorhabdus nematophila* K1 and *Bacillus thuringiensis* subsp. *Aizawai* against *Spodoptera exigua* (Lepidoptera: Noctuidae). Biological Control 39, 201-209.

Jurat-Fuentes, J.L., Adang, M.J., 2006. Cry toxin mode of action in susceptible and resistant *Heliothis virescens* larvae. Journal of Invertebrate Pathology 92, 166-171.

Jurat-Fuentes, J.L., Jackson, T.A., 2012. Bacterial entomopathogens. In: Vega, F.E., Kaya, H.K. (Eds.), Insect Pathology, 2nd Edition. Academic Press, San Diego. pp. 265-349.

Kabaluk, J.T., Ericsson, J.D., 2007. *Metarhizium anisopliae* seed treatment increases yield of field corn when applied for wireworm control. Agronomy Journal 99, 1377-1381.

Kabaluk, T., Gazdik, K., 2005 Directory of microbial pesticides for agricultural crops in OECD countries. http://www.organicagcentre.ca/Docs/MicrobialDirectory-English-V237-05-Revision1.pdf

Kabaluk, T., Svircev, A., Goettel, M., Woo, S.G. (Eds.) 2010. Use and Regulation of Microbial Pesticides in Representative Jurisdictions Worldwide, IOBC Global, 108 pp.

Kambrekar, D. N., Kulkarni, D. A., Giraddi, R. S. 2007. An assessment of quality of HaNPV produced by private laboratories. Karnatica Journal of Agricultural Science 20, 417-419.

Kang, S.W., Lee, S.H., Yoon, C.S., Kim, S.W., 2005. Conidia production by *Beauveria bassiana* (for the biocontrol of diamondback moth) during solid-state fermentation in a packed-bed bioreactor. Biotechnology Letters 27, 135-139.

Kaplan, F., Alborn, H.T., von Reuss, S.H., Ajredini, R., Ali, J.G., Akyazi, F., Stelinski, L.L., Edison, A.S., Schroeder, F.C., Teal, P.E., 2012. Interspecific nematode signals regulate dispersal behavior. PLoS ONE 7(6), art. no. e38735.

Kapongo, J.-P., Shipp, J.L., Kevan, P.G., Broadbent, A.B., 2008a. Optimal concentration of *Beauveria bassiana* vectored by bumble bees in relation to pest and bee mortality in greenhouse tomato and sweet pepper. BioControl, 53, 797-812.

Kapongo, J.-P., Shipp, J.L., Kevan, P.G., Sutton, J.S., 2008b. Co-vectoring of *Beauveria bassiana* and *Clonostachys rosea* by bumble bees (*Bombus impatiens*) for control of insect pests and suppression of grey mould in greenhouse tomato and sweet pepper. Biological Control, 46, 508-514.

Kariuki, C.W., McIntosh, A.H., 1999. Infectivity studies of a new baculovirus isolate for control of diamondback moth (Plutellidae: Lepidoptera). Journal of Economic of Entomology 92, 1093-1098.

Kaya, H.K., Gaugler, R., 1993. Entomopathogenic nematodes. Annual Review of Entomology 38, 181-206.

Kaya, H. K., Lacey, L. A., 2007. Introuction to microbial control. In: Lacey, L.A., Kaya, H.K. (Eds.), Field Manual of Techniques in Invertebrate Pathology: Application and Evaluation of Pathogens for Control of Insects and Other Invertebrate Pests, 2nd Edition. Springer, Dordrecht, The Netherlands, pp. 3-7.

Kaya, H.K., Aguillera, M.M., Alumai, A., Choo, H.Y., de la Torre, M., Foder, A., Ganguly, S., Hazir, S., Lakatos, T., Pye, A., Wilson, M., Yamanaka, S., Yang, H., Ehlers, R.-U., 2006. Status of entomopathogenic nematodes and their symbiotic bacteria from selected countries or regions of the world. Biological Control 38, 134-155.

Keller, S., 2000. Use of *Beauveria brongniartii* in Switzerland and its acceptance by farmers. IOBC/WPRS Bulletin 23, 67-71.

Keller, S., David-Henriet, A.-I., Schweizer, C., 2000. Insect pathogenic soil fungi from *Melolontha melolontha* control sites in the canton Thurgau. IOBC/WPRS Bulletin 23, 73-78.

Keller, S., Kessler, P., Schweizer, C., 2003. Distribution of insect pathogenic soil fungi in Switzerland with special reference to *Beauveria brongniartii* and *Metarhizium anisopliae*. BioControl 48, 307-319.

Kennedy, G.G., 2008. Integration of insect-resistant genetically modified crops within IPM programs. In: Romeis, J., Shelton, A.M., Kennedy, G.G. (Eds.), Integration of Insect-Resistant, Genetically Modified Crops within IPM Programs. Springer, Dordrecht, The Netherlands, pp. 1-26.

Kepler, R.M., Bruck, D.J., 2006. Examination of the interaction between the black vine weevil (Coleoptera: Curculionidae) and an entomopathogenic fungus reveals a new tritrophic interaction. Environmental Entomology 35, 1021-11029.

Kerwin, J. L., Petersen, E. E., 1997. Fungi: Oomycetes and Chytridiomycetes. In: Lacey, L. A. (Ed.) Manual of Techniques in Insect Pathology. Academic Press, San Diegio, pp. 251-268.

Kevan, P.G., Kapongo, J.-P., Al-mazra'awi, M.S., Shipp, J.L., 2008. Honey bees, bumble bees, and biocontrol: New alliances between old friends. In: James, R.R., Pitts-Singer, T.L. (Eds.), Bee Pollination in Agricultural Eco-systems. Oxford University Press, pp. 65-79.

Khan, M. Q., Abbasi, M. W., Zaki, M. J., Khan, S. A., 2010. Evaluation of *Bacillus thuringiensis* isolates against root-knot nematodes following seed application in okra and mungbean. Pakistan Journal of Botany 42, 2903-2910.

Khan, S., Guo, L., Maimaiti, Y., Mijit, M., Qiu, D., 2012, Entomopathogenic fungi as microbial biocontrol agents, Molecular Plant Breeding. 3, 63-79.

Kiewnick, S., 2001. Advanced fermentation and formulation technologies for fungal antagonists. In: Sikora, R.A. (Ed.), Tri-trophic Interactions in the Rhizosphere andRrootHhealth. IOBC/WPRS Bulletin 24, pp. 77-79.

Kiewnick, S., Sikora, R.A., 2006. Biological control of the root-knot nematode *Meloidogyne incognita* by *Paecilomyces lilacinus* strain 251. Biological Control 39, 179-187.Kikankie, C.K., Brooke, B.D., Knols, B.G.J., Koekemoer, L.L., Farenhorst, M., Hunt, R.H., Thomas, M.B., Coetzee, M., 2010. The infectivity of the entomopathogenic fungus *Beauveria bassiana* to insecticide-resistant and susceptible *Anopheles arabiensis* mosquitoes at two different temperatures. Malaria Journal 9, 71-80.

Kim, J. J., Goettel, M. S., Gillespie, D. R., 2009. Evaluation of *Lecanicillium longisporum*, Vertalec® against the cotton aphid, *Aphis gossypii*, and cucumber powdery mildew, *Sphaerotheca fuliginea* in a greenhouse environment. Crop Protection 29, 540-544.

Klein, M.G., 1990. Efficacy against soil-inhabiting insect pests. In: Gaugler, R., Kaya, H.K. (Eds.), Entomopathogenic Nematodes in Biological Control. CRC Press, Boca Raton, FL, pp. 195-214.

Klein, M.G., 1992. Use of *Bacillus popilliae* in Japanese beetle control. In: Jackson, T.A., Glare, T.R. (Eds.), Use of Pathogens in Scarab Pest Management. Intercept Limited, Hampshire, UK, pp. 179-189.

Klein, M.G., Grewal, P.S., Jackson, T.A., Koppenhöfer, A.M., 2007. Lawn turf and grassland pests. In: Lacey, L.A., Kaya, H.K. (Eds.), Field Manual of Techniques in Invertebrate Pathology: Application and Evaluation of Pathogens for Control of Insects and Other Invertebrate Pests, 2nd Edition. Springer, Dordrecht, The Netherlands, pp. 655-675.

Klingen, I., Haukeland, S., 2006. The soil as a reservoir for natural enemies of pest insects and mites with emphasis on fungi and nematodes. In: Eilenberg, J., Hokkanen, H.M.T. (Eds.), An Ecological and Societal Approach to Biological Control. Springer, The Netherlands, pp 145-211.

Klingen, I., Eilenberg, J., Meadow, R., 2002a. Effects of farming system, field margins and bait insect on the occurrence of insect pathogenic fungi in soils. Agriculture, Ecosystems and Environment 91, 191-198.

Klingen, I., Hajek, A., Meadow, R., Renwick, J.A.A.A., 2002b. Effect of brassicaceous plants on the survival and infectivity of insect pathogenic fungi. BioControl 47, 411-425.

Knight, A. L., Witzgall, P., 2013. Combining mutualistic yeast and pathogenic virus — a novel method for codling moth control. Journal of Chemical Ecology 39, 1019-1026.

Knowles, B.H., Ellar, D.J., 1987. Colloid-osmotic lysis is a general feature of the mechanism of action of *Bacillus thuringiensis*-endotoxins with different insect specificity. Biochimica et Biophysica Acta 924, 507-518.

Koike, M., Shinya, R., Aiuchi, D., Mori, M., Ogino, R., Shinomiya, H., Tani, M. Goettel, M., 2011. Future biological control for soybean cyst nematode, in: El-Shemy, H. A. (Ed). Soybean Physiology and Biochemistry, Intech, Croatia, pp 193 -208.

Kolodny-Hirsch, D. M., Sitchawat, T., Jansiri, T., Chenrchaivachirakul, A., Ketunuti, U., 1997. Field evaluation of a commercial formulation of the *Spodoptera exigua* (Lepidoptera: Noctuidae) nuclear polyhedrosis virus for control of Beet Armyworm on vegetable crops in Thailand. Biocontrol Science and Technology 7, 475-488.

Koppenhöfer, A.M., Fuzy, E.M., 2002. Comparison of neonicotinoid insecticides as synergists for entomopathogenic nematodes. Biological Control 24, 90-97.

Koppenhöfer, A.M., Fuzy, E.M., 2003. Ecological characterization of *Steinernema scarabaei*, a scarab-adapted entomopathogenic nematode from New Jersey. Journal of Invertebrate Pathology 83, 139-148.

Koppenhöfer, A.M., Fuzy, E.M., 2007. Soil moisture effects and persistence of the entomopathogenic nematodes *Steinernema scarabaei, S. glaseri, Heterorhabditis zealandica,* and *H. bacteriophora*. Applied Soil Ecology 35, 128-139.

Koppenhöfer, A.M., Fuzy, E.M., 2008. Effect of the anthranilic diamide insecticide, chlorantraniliprole, on *Heterorhabditis bacteriophora* (Rhabditida: Heterorhabditidae) efficacy against white grubs (Coleoptera: Scarabaeidae). Biological Control 45, 93-102.

Koppenhöfer, A.M., Choo, H.Y., Kaya, H.K., Lee, D.W., Gelernter, W.D., 1999. Increased field and greenhouse efficacy against scarab grubs with a combination of an entomopathogenic nematode and *Bacillus thuringiensis*. Biological Control 14, 37–44.

Koppenhöfer, A.M., Grewal, P.S., Fuzy, E.M., 2006. Virulence of the entomopathogenic nematodes *Heterorhabditis bacteriophora, H. zealandica,* and *Steinernema scarabaei* against five white grub species (Coleoptera: Scarabaeidae) of economic importance in turfgrass in North America. Biological Control 38, 397-404.

Koppenhöfer, A.M., Grewal, P.S., Fuzy, E.M., 2007. Differences in penetration routes and establishment rates of four entomopathogenic nematode species into four white grub species. Journal of Invertebrate Pathology 94, 184-195.

Koppenhöfer, A.M., Grewal, P.S., Fuzy, E.M., 2009. Long-term effects and persistence of *Steinernema scarabaei* applied for suppression of *Anomala orientalis* (Coleoptera: Scarabaeidae). Biological Control 48, 63-72.

Koppenhöfer, A.M., Jackson, T. A., Klein, M. G., 2012. Bacteria for use against soil-inhabiting insects In: Lacey, L.A. (Ed.), Manual of Techniques in Invertebrate Pathology. Academic Press, San Diego. pp. 129-149.

Kouassi, M., Coderre, D., Todorova, S.I., 2003. Effect of plant type on the persistence of *Beauveria bassiana*. Biocontrol Science and Technology 13, 415-427.

Kreutz, J., Zimmermann, G., Vaupel, O., 2004. Horizontal transmission of the entomopathogenic fungus *Beauveria bassiana* among the spruce bark beetle, *Ips typographus* (Col., Scolytidae), in the laboratory and under field conditions. Biocontrol Science and Technology 14, 837-848.

Kreig, A., Huger, A.M., Langenbruch, G.A., Schnetter, W., 1983. *Bacillus thuringiensis* var. *tenebrionis*: Ein neuer, gegenüber Larven von Coleopteren wirksamer Pathotyp. Zeitschrift für Angewandte Entomologie 96, 500-508.

Krishna, C., 2005. Solid-state fermentation systems–an overview. Critical Reviews in Biotechnology 25, 1-30.

Krishna,V. V., Qaim, M. 2012. Bt cotton and sustainability of pesticide reductions in India. Agricultural Systems107, 47-55.

Kroschel, J., Lacey, L.A. (Eds.), 2008. Integrated Pest Management for the Potato Tuber Moth, *Phthorimaea operculella* (Zeller)–a Potato Pest of Global Importance. Tropical Agriculture 20, Advances in Crop Research 10. Margraf Publishers, Weikersheim, Germany, 147 pp.

Kumar, S., Chandra, A., Pandey, K.C., 2008. *Bacillus thuringiensis* (Bt) transgenic crop: an environment friendly insect-pest management strategy. Journnal of Environmental Biology 29, 641-653.

Kunkel, B.A., Shapiro-Ilan, D.I., Campbell, J.F., Lewis, E.E., 2006. Effect of *Steinernema glaseri*-infected host exudates on movement of conspecific infective juveniles. Journal of Invertebrate Pathology 93, 42-49.

Kunimi, Y., 2007. Current status and prospects on microbial control in Japan. Journal of Invertebrate Pathology 95, 181-186.

Labbé, R.M., Gillespie, D.R., Cloutier, C., Brodeur, J., 2009. Compatibility of an entomopathogenic fungus with a predator and a parasitoid in the biological control of greenhouse whitefly. Biocontrol Science and Technology 19, 429-446.

Lacey, L.A., 2007. *Bacillus thuringiensis* serovariety *israelensis* and *Bacillus sphaericus* for mosquito control. Bulletin of the American Mosquito Control Association 7, 133-163.

Lacey, L. A., Arthurs, S.P. 2005. New method for testing solar sensitivity of commercial formulations of the granulovirus of codling moth (*Cydia pomonella*, Tortricidae: Lepidoptera). Journal of Invertebrate Pathology 90, 85-90.

Lacey, L.A., Kaya, H.K. (Eds.), 2007. Field Manual of Techniques in Invertebrate Pathology: Application and Evaluation of Pathogens for Control of Insects and Other Invertebrate Pests, 2nd Edition. Springer, Dordrecht, The Netherlands, 868 pp.

Lacey, L.A., Merritt, R.W., 2003. The safety of bacterial microbial agents used for black fly and mosquito control in aquatic environments. In: Hokkanen, H.M.T., Hajek, A.E. (Eds.), Environmental Impacts of Microbial Insecticides: Need and Methods for Risk Assessment. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 151-168.

Lacey, L.A., Shapiro-Ilan, D.I., 2008. Microbial control of insect pests in temperate orchard systems: potential for incorporation into IPM. Annual Review of Entomology 53, 121-144.

Lacey, L.A., Siegel, J.P., 2000. Safety and ecotoxicology of entomopathogenic bacteria. In: Charles, J.-F., Delecluse, A., Nielsen-LeRoux, C. (Eds.), Entomopathogenic Bacteria: From Laboratory to Field Application. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 253–273.

Lacey, L.A., Kroschel, J., 2009. Microbial control of the potato tuber moth (Lepidoptera: Gelechiidae). Fruit, Vegetable, and Cereal Science and Biotechnology 3, 46-54.

Lacey, L.A., Amaral, J.J., Klein, M.G., Simões, N.J., Martins, A., Mendes, C., 1994. Microbial control of *Popillia japonica* (Coleoptera: Scarabaeidae) on Terceira. International Colloquium on Invertebrate Pathology and Microbial Control, Society for Invertebrate

Pathology, August 28-September 2, 1994. Montpellier, France, pp. 409-415.

Lacey, L. A., Fransen, J.J., Carruthers, R., 1996. Global distribution of naturally occurring fungi of *Bemisia*, their biologies and use as biological control agents. In: Gerling, D., Mayer, R., (Eds.). *Bemisia* 1995: Taxonomy, Biology, Damage, and Management. Intercept, Andover, UK, pp. 401-433.

Lacey, L.A., Frutos, R., Kaya, H.K., Vail, P., 2001. Insect pathogens as biological control agents: do they have a future? Biological Control 21, 230-248.

Lacey, L.A., Arthurs, S.P., Knight, A., Becker, K., Headrick, H., 2004. Efficacy of codling moth granulovirus: effect of adjuvants on persistence of activity and comparison with other larvicides in a Pacific Northwest apple orchard. Journal of Entomological Science 39, 500-513.

Lacey, L.A., Neven, L.G, Headrick, H.L., Fritts, R. Jr., 2005. Factors affecting entomopathogenic nematodes (Steinernematidae) for control of overwintering codling moth (Lepidoptera: Torticidae) in fruit bins. Journal of Economic Entomology 98, 1863-1869.

Lacey, L.A., Arthurs, S.P., Granatstein, D., Headrick, H., Fritts, R. Jr., 2006a. Use of entomopathogenic nematodes (Steinernematidae) in conjunction with mulches for control of codling moth (Lepidoptera: Torticidae). Journal of Entomological Science 41, 107-119.

Lacey, L.A., Arthurs, S.P., Unruh, T.R., Headrick, H., Fritts, R. Jr., 2006b. Entomopathogenic nematodes for control of codling moth (Lepidoptera: Tortricidae) in apple and pear orchards: effect of nematode species and seasonal temperatures, adjuvants, application equipment and post-application irrigation. Biological Control 37, 214–223.

Lacey, L.A., Arthurs, S.P., Knight, A., Huber, J., 2007. Microbial control of lepidopteran pests of apple orchards. In: Lacey, L.A., Kaya, H.K. (Eds.), Field Manual of Techniques in

Invertebrate Pathology: Application and Evaluation of Pathogens for Control of Insects and Other Invertebrate Pests, 2nd Edition. Springer, Dordrecht. pp. 527-546.

Lacey, L.A., Headrick, H.L., Arthurs, S.P., 2008a. The effect of temperature on the long-term storage of codling moth granulovirus formulations. Journal of Economic Entomology 101, 288-294.

Lacey, L.A., Thomson, D., Vincent, C., Arthurs, S.P., 2008b. Codling moth granulovirus: a comprehensive review. Biocontrol Science and Technology 18, 639-663.

Lacey, L.A., Kroschel, J., Wraight, S.P., Goettel, M.S., 2009a. An introduction to microbial control of insect pests of potato. Fruit, Vegetable, and Cereal Science and Biotechnology 3, 20–24.

Lacey, L.A., Headrick, H.L., Horton, D.R., Schriber, A., 2010a. Effect of granulovirus on the mortality and dispersal of potato tuber worm (Lepidoptera: Gelechiidae) in refrigerated storage warehouse conditions. Biocontrol Science and Technology 20, 437-447.

Lacey, L.A., Shapiro-Ilan, D.I., Glenn, G.M., 2010b. The effect of post-application anti-desiccant agents and formulated host-cadavers on entomopathogenic nematode efficacy for control of diapausing codling moth larvae (Lepidoptera: Tortricidae). Biocontrol Science and Technology. 20, 909-921.

Lacey, L. A., Liu, T.-X., Buchman, J. L., Munyaneza, J. E., Goolsby, J. A., Horton, D.R., 2011. Entomopathogenic fungi (Hypocreales) for control of potato psyllid, *Bactericera cockerelli* (Šulc) (Hemiptera: Triozidae) in an area endemic for zebra chip disease of potato. Biological Control 36, 271-278.

Langenbruch, G. A. , Krieg, A., Huger, A. M. , Schnetter, W., 1985. Erst Feldversuche zur Bekämpfung der Larven des Kartoffelkäfers (*Leptinotarsa decemlineata*) mit *Bacillus* *thuringiensis* var. *tenebrionis*. Mededelingen Faculteit Landbouwkunde, Rijksuniversiteit Gent 50, 441-449.

Längle, T., Pernfuss, B., Seger, C., Strasser, H., 2005. Field efficacy evaluation of *Beauveria brongniartii* against *Melolontha melolontha* in potato cultures. Sydowia 57, 54-93.

Lapointe, R., Thumbi, D.K., Lucarotti, C.J., 2012. Recent advances in our knowledge of baculovirus molecular biology and its relevance for the registration of baculovirus-based products for insect pest population control. In: Soloneski, S. and Larramendy, M. L., (Eds) Integrated Pest Management and Pest Control, ISBN 978-953-307-926-4InTech Open Access Publisher, Rijeka, Croatia. Chapter 21: Pp. 481-522.

Lasa, R.C., Pagola, I., Ibanez, J.E., Belda, J.E., Caballero, P., Williams, T., 2007. Efficacy of *Spodoptera exigua* multiple nucleopolyhedrovirus (SeMNPV) as a biological insecticide for beet armyworm in greenhouses in Southern Spain. Biocontrol Science and Technology 17, 221-232.

Lasa, R., Williams, T., Caballero, P., 2008. Insecticidal properties and microbial contaminants in a *Spodoptera exigua* multiple nucleopolyhedrovirus (Baculoviroidae) formulation stored at different temperatures. Journal of Economic Entomology 101, 42-49.

Lebel. G., Vachon, V., Préfontaine, G., Girard, F,, Masson, L., Juteau, M., Bah, A., Larouche, G., Vincent, C., Laprade, R., Schwartz, J.L., 2009. Mutations in domain I interhelical loops affect the rate of pore formation by the *Bacillus thuringiensis* Cry1Aa toxin in insect midgut brush border membrane vesicles. Applied and Environmental Microbiology. 75,3842-3850.

Leland, J.E., Mullins, D.E., Vaughan, L., Warren, H.L., 2005a. Effects of media composition on submerged culture spores of the entomopathogenic fungus, *Metarhizium anisopliae* var.

acridum, part 1: comparison of cell wall characteristics and drying stability among three spore types. Biocontrol Science and Technology 15, 379-392.

Leland, J.E., Mullins, D.E., Vaughan, L., Warren, H.L., 2005b. Effects of media composition on submerged culture spores of the entomopathogenic fungus, *Metarhizium anisopliae* var. *acridum*, part 2: effects of media osmolality on cell wall characteristics, carbohydrate concentrations, drying stability, and pathogenicity. Biocontrol Science and Technology 15, 393-409.

Leuschner, R.G.K., Robinson, T.P., Hugas, M., Sandro Cocconcelli, P., Richard-Forget, F., Klein, G., Licht, T.R., Nguyen-The, C., Querol, A., Richardson, M., Suarez, J.E., Thrane, U. Vlak, J.M., von Wright, A., 2010. Qualified presumption of safety (QPS): a generic risk assessment approach for biological agents notified to the European Food Safety Authority (EFSA). Trends in Food Science and Technology 21, 425-435.

Lewis, E.E., Grewal, P.S., 2005. Interactions with plant parasitic nematodes. In: Grewal, P.S., Ehlers, R.-U., Shapiro-Ilan, D.I. (Eds.), Nematodes as Biocontrol Agents. CABI, Wallingford, UK, pp. 349-362.

Lewis, E.E., Grewal, P.S., Sardanelli, S., 2001. Interactions between the *Steinernema feltiae-Xenorhabdus bovienii* insect pathogen complex and the root-knot nematodes *Meloidogyne incognita*. Biological Control 21, 55-62.

Li, D.P., Holdom, D.G., 1993. Effect of soil matric potential on sporulation and conidial survival of *Metarhizium anisopliae* (Deuteromycotina: Hyphomycetes). Journal of Invertebrate Pathology 62, 73-277.

Li, J., Carrol, J., Ellar, D.J., 1991. Crystal structure of insecticidal δ-endotoxin from *Bacillus thuringiensis* at 2.5 Å resolution. Nature 353, 815–821.

Li, X.Q., Tan, A., Voegtline, M., Bekele, S., Chen, C.S., Aroian, R.V., 2008. Expression of Cry5B protein from *Bacillus thuringiensis* in plant roots confers resistance to root-knot nematode. Biological Control 47, 97-102.

Lisansky, S. 1997. Microbial biopesticides. In: Evans H.F. (Ed.) Microbial Insecticides; novelty or necessity. BCPC Symposium proceedings No.68. British Crop Protection Council. Farnham,, UK, pp. 3-11.

Lisansky, S. G., Quinlan, R., Tassoni, G., 1993. The *Bacillus thuringiensis* Production Handbook: laboratory methods, manufacturing, quality control, registration. CPL Press, Newberry, UK.

Liu, S., Li, H., Sivakumar, S., Boning, B. C., 2006. Virus derived genes for insect resistant transgenic plants. In: Bonning B.C. (Ed.), Advances in Virus Research Volume 68, Insect Viruses: Biotechnological Applications. Academic Press, San Diego, pp. 427-457.

Liu, S.F., Chen, S.Y., 2005. Efficacy of the fungi *Hirsutella minnesotensis* and *Hirsutella rhossiliensis* from liquid culture for control of *Heterodera glycines*. Nematology 7, 149-157.

Llàcer, E., Martinez de Altube, M.M., Jacas, J.A., 2009. Evaluation of the efficacy of *Steinernema carpocapsae* in a chitosan formulation against the red palm weevil, *Rhynchophorus ferrugineus*, in *Phoenix canariensis*. BioControl 54, 559-565.

Lomer, C.J., Bateman, R.P., Dent, D., De Groote, H., Douro-Kpindou, O.K., Kooyman,C., Langewald, J., Ouambama,Z., Peveling, R., Thomas, M., 1999. Development of strategies for the incorporation of biological pesticides into the integrated management of locusts and grasshoppers. Agricultural and Forest Entomology 1, 71-88.

Lomer, C.J., Bateman, R.P. Johnson, D.L., Langewald, J., Thomas, M. 2001. Biological control of locusts and grasshoppers. Annual Review of Entomology 46, 667-702.

Lorang, J.M., Tuori, R.P., Martinez, J.P., Sawyer, T.L., Redman, R.S, Rollins, J.A., Wolpert, T.J., Johnson, K.B, Rodriquez, R.J., Dickman, M.B., Ciuffetti, L.M., 2001. Green fluorescent protein is lighting up fungal biology. Applied and Environmental Microbiology 67, 1987-1994.

Lord, J.C., Campbell, J.F., Sedlacek, J.D., Vail, P.V., 2007. Application and evaluation of entomopathogens for managing insects in stored products. In: Lacey, L.A., Kaya, H. K. (Eds.), Field Manual of Techniques in Invertebrate Pathology: Application and Evaluation of Pathogens for Control of Insects and Other Invertebrate Pests, 2nd Edition. Springer, Dordrecht, The Netherlands, pp. 677-693.

Losey, J.E., Rayor, L.S., Carter, M.E., 1999. Transgenic pollen harms monarch larvae. Nature 399, 214.

Loya, L.J., Hower, A.A., 2002. Population dynamics, persistence, and efficacy of the entomopathogenic nematode *Heterorhabditis bacteriophora* (Oswego strain) in association with the clover root curculio (Coleoptera: Curculionidae) in Pennsylvania. Environmental Entomology 31, 1240-2150.

Lucarotti, C.J., Moreau, G., Kettela, E.G., 2007. Abietiv™, a viral biopesticide for control of the balsam fir sawfly. In: Vincent, C., Goettel, M.S., Lazarovits G., (Eds.), Biological Control: A Global Perspective. CAB Iinternational, Wallingford, UK, pp. 353-361.

Maniania, N.K., 2002. A low-cost contamination device for infecting adult tsetse, *Glossina* spp., with the entomopathogenic funguus *Metarhizium anisopliae* in the field. Biocontrol Science and Technology 12, 59-66.

Maniania, N.K., Nchu, F., Ekesi, S., 2007. Fungal pathogens for biocontrol of ticks. In: Ekesi, S., Maniania, N.K. (Eds.), Use of Entomopathogenic Fungi in Biological Pest Management. Research Signpost, Kerala, India, pp. 275-294.

Marrone, P. G., 2007. Barriers to adoption of biological control agents and biological pesticides. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources 2, No. 051. doi: 10.1079/PAVSNNR20072051, On line ISSN 1749-8848, http://www.cababstractsplus.org/cabreviews

Martignoni, M.E., 1999. History of TM Biocontrol: the first registered virus based product for insect control of a forest insect. American Entomologist 45, 30-37.

Martin, K.J., 2007. Introduction to molecular analysis of ectomycorrhizal communities. Soil Science Society of America Journal 71, 601-610.

Martin, P. A., Gundersen-Rindal, D., Blackburn, M., Buyer, J., 2007a. *Chromobacterium subtsugae* sp. nov., a betaproteobacterium toxic to Colorado potato beetle and other insect pests. International Journal of Systematic and Evolutionary Microbiology 57, 993-999.

Martin, P. A., Hirose, E., Aldrich, J. R., 2007b. Toxicity of *Chromobacterium subtsugae* to southern green stink bug (Heteroptera: Pentatomidae) and corn rootworm (Coleoptera: Chrysomelidae). Journal of Economic Entomology. 100, 680-684.

Martinez, A.M., Caballero, P., Villanueva, M., Miralles, N., San-Martin, I., Lopez, E., Williams, T., 2004. Formulation with an optical brightener does not increase probability of developing resistance to *Spodoptera frugiperda* nucleopolyhedrovirus in the laboratory. Journal of Economic Entomology 97, 1202-1208.

Martinez del Altube, M.D.M., Strauch, O., Fernandez De Castro, G., Pena, A.M., 2008. Control of the flat-headed root borer *Capnodis tenebrionis* (Linne) (Coleoptera: Buprestidae) with the entomopathogenic nematode *Steinernema carpocapsae* (Weiser) (Nematoda: Steinernematidae) in a chitosan formulation in apricot orchards. Biocontrol 53, 531-539.

Marvier, M., McCreedy, C., Regetz, J., Kareiva, P., 2007. A meta-analysis of effects of Bt cotton and maize on nontarget invertebrates. Science 316, 1475-1477.

Marx-Stoelting, P., Pfeil, R., Solecki, R., Ulbrich, B., Grote, K., Ritz, V., Banasiak, U., Heinrich-Hirsch, B., Moeller, T., 2011. Assessment strategies and decision criteria for pesticides with endocrine disrupting properties relevant to humans. Reproductive Toxicology 31, 574-584.

Mashtoly, T. A., Abolmaaty, A., Thompson, N., El-Said El-Zemaity, M., Hussien, M. I., Alm, S. R., 2010. Enhanced toxicity of *Bacillus thuringiensis japonensis* strain Buibui toxin to oriental beetle and northern masked chafer (Coleoptera: Scarabaeidae) larvae with *Bacillus* sp. NFD2. Journal of Economic Entomology 103, 1547–1554.

Mashtoly, T.A., Abolmaaty, A., El-Said El-Zemaity, M., Hussien, M.I., Alm, S.R., 2011. Enhanced toxicity of *Bacillus thuringiensis* subspecies *kurstaki* and *aizawai* to black cutworm larvae (Lepidoptera: Noctuidae) with *Bacillus* sp. NFD2 and *Pseudomonas* sp. FNFD1. Journal of Economic Entomology 104, 41-46.

Masson, L., Tabashnik, B.E., Liu, Y.B., Brousseau, R., Schwartz, J.L., 1999. Helix 4 of the *Bacillus thuringiensis* Cry1Aa toxin lines the lumen of the ion channel. Journal of Biological Chemistry 274, 31996-32000.

Mbata, G.N., Shapiro-Ilan, D.I., 2005. Laboratory evaluation of virulence of heterorhabditid nematodes to *Plodia interpunctella* Hubner (Lepidoptera: Pyralidae). Environmental Entomology 34, 676-682.

McCoy, C.W., Samson, R.A., Boucias, D.G., Osborne, L.S., Peña, J., Buss, L.J., 2009. Pathogens Infecting Insects and Mites of Citrus. LLC Friends of Microbes. Winter Park, FL, USA. 193 pp.

McCrevy, K. W., 2008. Conservation biological control. In: Capinera, J. L. (Ed.), Encyclopedia of Entomology 2nd ed. SpringerDordrecht, The Netherlands, pp. 1021-1023.

McDougall, P., 2013. The cost and time involved in the discovery, development and authorisation of a new plant biotechnology derived trait. Croplife International . 24 pp. http://www.croplife.org/PhillipsMcDougallStudy

McGaughey, W. H., 1985. Insect resistance to the biological insecticide *Bacillus thuringiensis*. Science 229, 193-195.

McGaughey, W. H., 1994. Problems of insect resistance to *Bacillus thuringiensis.* Agriculture, Ecosystems and Environment 49, 95-102.

McGuire, M.R., Tamez-Guerra, P., Behle, R.W., Streett, D.A., 2001. Comparative field stability of selected entomopathogenic virus formulations. Journal of Economic Entomology 94, 1037-1044.

McGuire, M.R., Leland, J.E., Dara, S.K., Park, Y.-H., Ulloa, M., 2006. Effect of different isolates of *Beauveria bassiana* on field populations of *Lygus hesperus*. Biological Control 38, 390-396.

Meekers, E. T. M., Faransen, J. J., van Lenteren, J. C., 2002. Pathogenicity of *Aschersonia* spp. against whiteflies *Bemisia argentifolii* and *Trialeurodes vaporariorum*. Journal of Invertebrate Pathology 81, 1-11.

Meeussen, J.J. 2012. OECD guidelines and harmonization for microbial control agents. In: Sundh, I., Wilcks, A., Goettel, M.S. (Eds). Beneficial Microorganisms in Agriculture, Food and the Environment. CABI international, Wallingford, UK. pp 308-321.

Mensah, R.K., Liang, W., Gibb, D., Coates, R., Johnson, D., 2005. Improving efficacy of nuclear polyhedronsis virus and *Bacillus thuringiensis* against *Helicoverpa* spp. with ultra-violet light protected petroleum spray oils on cotton in Australia. International Journal of Pest Management 51, 101-109.

Metz, M., (Ed.), 2003. *Bacillus thuringiensis*: a cornerstone of modern agriculture. Journal of New Seeds 5, no. 1-3.

Meyling, N.V., Eilenberg, J., 2006a. Isolation and characterisation of *Beauveria bassiana* isolates from phylloplanes of hedgerow vegetation. Mycological Research 110, 188-195.

Meyling, N.V., Eilenberg, J., 2006b. Occurrence and distribution of soil borne entomopathogenic fungi within a single organic agroecosystem. Agriculture Ecosystems and Environment 113, 336-341.

Meyling, N.V., Pell, J.K. 2006c. Detection and avoidance of an entomopathogenic fungus by a generalist insect predator. Ecological Entomology 31, 162-171.

Meyling, N.V., Eilenberg, J., 2007. Ecology of the entomopathogenic fungi *Beauveria bassiana* and *Metarhizium anisopliae* in temperate agroecosystems: Potential for conservation biocontrol. Biological Control 43, 145-155.

Meyling, N.V., Hajek, A.E., 2010. Principles from community and matapopulation ecology: application to fungal entomopatogens. BioControl 55, 39-54.

Meyling, N., Pell, J.K., Eilenberg, J., 2006. Dispersal of *Beauveria bassiana* by the activity of nettle insects. Journal of Invertebrate Pathology 93, 121-126.

Meyling, N.V., Lübeck, M., Buckley, E.P., Eilenberg, J., Rehner, S.A., 2009. Community composition, host range and genetic structure of the fungal entomopathogen *Beauveria* in adjoining agricultural and seminatural habitats. Molecular Ecology 18, 1282-1293.

Migiro, L.N., Maniania, N.K., Chabi-Olaye, A., Vandenberg, J., 2010. Pathogenicity of entomopathogenic fungi *Metarhizium anisopliae* and *Beauveria bassiana* (Hypocreales: Clavicipitaceae) isolates to the adult pea leafminer (Diptera: Agromyzidae) and prospects of an autoinoculation device for infection in the field. Environmental Entomology 39, 468-475.

Millar, L.C., Barbercheck, M.E., 2001. Interaction between endemic and introduced entomopathogenic nematodes in conventional-till and no-till corn. Biological Control 22, 235-245.

Miller, L.K., (Ed.), 1997. The Baculoviruses. Plenum Press, New York, 477 pp.

Miller, L.K., Ball, L.A., (Eds.), 1998. The Insect Viruses. Plenum Press, New York, 411 pp.

Milner, R.J., Samson, P., Morton, R., 2003. Persistence of conidia of *Metarhizium anisopliae* in sugarcane fields: Effect of isolate and formulation on persistence over 3.5 years. Biocontrol Science and Technology 13, 507-516.

Minorsky, P.V., 2001. The hot and the classic. The monarch butterfly controversy. Plant Physiology 127, 709–710.

Moar, W.J., Puzstai-Carey, M., Van Faassen, H., Bosh, D., Frutos, R., Rang, C., Luo, K., Adang, M.J., 1995. Development of *Bacillus thuringiensis* CryIC resistance by *Spodoptera exigua*, (Hübner) (Lepidoptera: Noctuidae). Applied and Environmental Microbiology 61, 2086-2092.

Mohan, S., Raman, R., Gaur, H.S., 2003. Foliar application of *Photorhabdus luminescens,* symbiotic bacteria from entomopathogenic nematode *Heterorhabditis indica*, to kill cabbage butterfly *Pieris brassicae*. Current Science 84, 1397.

Monobrullah, M.D., Nagata, M., 2001. Optical brighteners as ultraviolet protectants and as enhancers in pathogenicity of *Spodoptera litura* (Fabricius) (Lep., Noctuidae) nucleopolyhedrovirus. Journal of Applied Entomology 125, 377-382.

Montesinos, E., 2003. Development, registration and commercialization of microbial pesticides for plant protection. International Microbiology 6, 245-252.

Moore, D., 2008. A plague on locusts–the LUBILOSA story. Outlooks on Pest Management 19, 14-17.

Moore, S.D., Kirkman, W., Stephen, P., 2004a. Crytogran: a virus for biological control of false codling moth. South African Fruit Journal 7, 56-60.

Moore, S.D, Pittaway, T., Bouwer, G., Fourie, J.G., 2004b. Evaluation of *Helicoverpa armigera* Nucleopolyhedrovirus (HearNPV) for control of *Helicoverpa armigera* (Lepidoptera: Noctuidae) on citrus in South Africa. Biocontrol Science and Technology 14, 239-250.

Morales, L., Moscardi, F., Sosa-Gomez, D.R., Paro, F.E., Soldorio, I.L., 2001. Fluorescent brighteners improve *Anticarsia gemmatalis* (Lepidoptera: Noctuidae) nucleopolyhedrovirus (AgMNPV) activity on AgMNPV-susceptible and resistant strains of the insect. Biological Control 20, 247-253.

Morales-Ramos, J.A., Guadalupe Rojas, M., Shapro-Ilan D.L. (Eds.), 2014. Mass Production of Beneficial Organisms. Elsevier, Amsterdam. pp. 483-517.

Moreau, G., Lucarotti, C.J., 2007. A brief review of the past use of baculoviruses for the management of euruptive forest defoliators and recent developments on a sawfly virus in Canada. The Forest Chronicle 83, 105-112.

Morse, R.J., Yamamoto, T., Stroud, R.M., 2001. Structure of Cry2Aa suggests an unexpected receptor binding epitope. Structure 9, 409-417.

Morton, A., Garcia-del-Pino, F., 2008. Field efficacy of the entomopathogenic nematode *Steinernema feltiae* against the Mediterranean flat-headed rootborer *Capnodis tenebrionis*. Journal of Applied Entomology 132, 632-637.

Moscardi, F., 1999. Assessment of the application of baculoviruses for the control of Lepidoptera. Annual Review of Entomology 44, 257-289.

Moscardi, F., 2007. Development and use of the nucleopolyhedrovirus of the velvetbean caterpillar in soybeans. In: Vincent, C., Goettel, M.S., Lazarovits, G. (Eds.), Biological Control: A Global Perspective. CAB International, Wallingford, UK, pp. 344-353.

Moscardi, F., Sosa-Gomez, D., 2007. Microbial control of insect pests of soybean In: Lacey, L.A., Kaya, H.K. (Eds.), Field Manual of Techniques in Invertebrate Pathology: Application and Evaluation of Pathogens for Control of Insects and Other Invertebrate Pests, 2nd Edition. Springer, Dordrecht, The Netherlands, pp. 411-426.

Moscardi, F., de Souza, M.L., de Castro, M. E.B., Moscardi, M.L., Szewczyk, B., 2011. Baculovirus pesticides: present state and future perspectives. In: Ahmad, I., Ahmad, F., Pichtel, J. (Eds.) Microbes and Microbial Technology. Springer, Dordrecht. pp. 415-445.

Moshayov, A., Koltai, H., Glazer, I., 2013. Molecular characterisation of the recovery process in the entomopathogenic nematode *Heterorhabditis bacteriophora*. International Journal for Parasitology 43, 843-852.

Mudgal, S., De Toni, A., Tostivint, C., Hokkanen, H., Chandler, D., 2013. Scientific support, literature review and data collection and analysis for risk assessment on microbial organisms used as active substance in plant protection products –Lot 1 Environmental Risk characterization. EFSA supporting publications 2013:EN-518. 149 pp. Available online: www.efsa.europa.eu/publications.

Mumm, R., 2013. A look at product development with genetically modified crops: examples from maize. Journal of Agriculture and Food Chemistry 61, 8254–8259.

Murray, D., Ferguson, J., Lloyd, R., Hopkinson, J., Maclean, S., Powell, R., 2001. Advances in *Heliothis* management on grain sorghum in Australia. In: Borrell A.K., Henzell R.G. (Eds.), Proceedings of the Fourth Australian Sorghum Conference, 2001. Kooralbyn, University of Queensland, Australia.

Murillo, R., Lasa, R., Goulson, D., Williams, T., Munoz, D., Caballero, P., 2003. Effect of Tinopal LPW on the insecticidal properties and genetic stability of the nucleopolyhedrovirus of *Spodoptera exigua* (Lepidoptera: Noctuidae). Journal of Economic Entomology 96, 1668-1674.

Nahar, P.B., Kulkarni, S.A., Kulye, M.S., Chavan, S.B., Kulkarni, G., Rajendran, A., Yadav, P.D., Shouche, Y., Deshpande, M.V., 2008. Effect of repeated *in vitro* sub culturing on the virulence of *Metarhizium anisopliae* against *Helicoverpa armigera* (Lepidoptera: Noctuidae). Biocontrol Science and Technology 18, 337-355.

Nair, K.S.S., Babjan, B., Sajeev, T.V., Sudheendrakumar, V.V., Mohamed-Ali, M.I., Varma, R.V., Mohandas, K., 1996. Field efficacy of nuclear polyhedrosis virus for protection of teak against the defoliator *Hyblea puera* Cramer (Lepidorptera: Hyblaeidae). Journal of Biological Control 10, 79-85.

Nakai, M., 2009. Biological control of Tortricidae in tea fields in Japan using insect viruses and parasitoids. Virologica Sinica 24, 323-332.

Nakai, M., Cuc, N.T.T., 2005. Field application of an insect virus in the Mekong Delta: Effects of a Vietnamese nucleopolyhedrovirus on *Spodoptera litura* (Lepidoptera: Noctuidae) and its parasitic natural enemies. Biocontrol Science and Technology 15, 443-453.

Nakai, M., Goto, C., Shiotsuki, T., Kunimi, Y., 2002. Granulovirus prevents pupation and retards development of *Adoxophyes honmai* larvae. Physiological Entomology 27, 157-164.

Neves, J.M., Teixeira, J.A., Simoes, N. Mota, M., 2001. Effect of airflow rate on yield of *Steinernema carpocapsae* Az 20 in liquid culture in an external-loop airlift bioreactor. Biotechnology and Bioengineering 72, 369-373.

Nguyen, Q., Qi, Y.M., Wu, Y., Chan, L.C.L., Nielsen, L.K., Reid, S., 2011. In vitroproduction of Helicoverpa baculovirus biopesticides—Automated selection of insect cell clones for manufacturing and systems biology studies. Journal of Virological Methods 175, 197-2005.Nielsen, C., Hajek, A. E., 2005. Control of invasive soybean aphid, *Aphis glycines* (Hemiptera: Aphididae), populations by existing natural enemies in New York State, with emphasis on entomopathogenic fungi. Environmental Entomology 34, 1036-1047.

Nielsen, A.L., Lewis, E.E., 2012. Designing the ideal habitat for entomopathogen use in nursery production. Pest Management Science 68, 1053-1061.

Nielsen, C., Jensen, A.B., Eilenberg, J., 2007. Survival of entomophthoralean fungi infecting aphids and higher flies during unfavourable conditions and implications for conservation biological control. In: Ekesi, S., Maniania, N.K. (Eds.), Use of Entomopathogenic Fungi in Biological Pest Management. Research Signpost, Kerala, India, pp. 13-38.

Nimkingrat, P., Khanam, S., Strauch, O., Ehlers, R.-U., 2013. Hybridisation and selective breeding for improvement of low temperature activity of the entomopathogenic nematode *Steinernema feltiae*. BioControl 58, 417-426.

Nyczepir, A., Shapiro-Ilan, D.I., Lewis, E.E., Handoo, Z., 2004. Effect of entomopathogenic nematodes on *Mesocriconema xenoplax* populations in peach and pecan. Journal of Nematology 36, 181-185.

O.E.C.D., 2002. Consensus document on information used in assessment of environmental applications involving baculoviruses. Series on harmonisation of regulatory oversight in biotechnology No. 20. ENV/JM/MONO(2002)1 OECD.

O'Callaghan, M., Brownbridge, M., 2009. Environmental impacts of microbial control agents used for control of invasive insects. In: Hajek, A.E., Glare, T.R., O'Callaghan, M. (Eds.), Use of Microbes for Control and Eradication of Invasive Arthropods. Springer, Dordrecht, The Netherlands, pp. 305-327.

O'Callaghan, M., Glare, T.R., Burgess, E.P.J., Malone, L.A., 2005. Effects of plants genetically modified for insect resistance on nontarget organisms. Annual Review of Entomology 50, 271–292.

Oestergaard, J., Belau, C., Strauch, O., Ester, A., Rozen, K. van, Ehlers, R.U., 2006. Biological control of *Tipula paludos* (Diptera: Nematocera) using entomopathogenic nematodes (*Steinernema* spp.) and *Bacillus thuring*iensis subsp. *israelensis*. Biological Control 39, 525-531.

Olleka, A., Mandour, N., Ren, S., 2009. Effect of host plant on susceptibility of whitefly *Bemisia tabaci* (Homoptera: Aleyrodidae) to the entomopathogenic fungus *Beauveria bassiana* (Ascomycota: Hypocreales). Biocontrol Science and Technology 19, 717-727.

Ortiz-Urquiza, A., Keyhani, N.O., 2013. Action on the surface: Entomopathogenic fungi *versus* the insect cuticle. Insects 4, 357-374.

Ownley, B.H., Pereira, R.M., Klingeman, W.E., Quigley, N.B., Leckie, B.M., 2004. *Beauveria bassiana*, a dual purpose biocontrol organism with activity against insect pests and plant pathogens, In: Lartey, R.T., Caesar, A.J. (Eds.), Emerging Concepts in Plant Health Management. Research Signpost, Kerala, India, pp 255-269.

Ownley, B.H., Gwinn, K.D., Vega, F.E., 2010. Endophytic fungal entomopathogens with activity against plant pathogens: ecology and evolution. BioControl 55, 113-128.

Panazzi, A.R., 2013. History and contemporary perspectives of the integrated pest management of soybean in Brazil. Neotropical Entomology 42, 119–127.

Papierok, B., Hajek, A. E., 1997. Fungi: Entomophthorales. In: Lacey, L.A. (Ed.), Manual of Techniques in Insect Pathology. Academic Press, San Diego. pp. 187-212.

Parsa S, Ortiz V, Vega, F.E., 2013. Establishing fungal entomopathogens as endophytes: towards endophytic biological control. Journal Visualized Experiments. e50360.

Pava-Ripoll, M., Posada, F.J., Momen, B., Wang, C., St. Leger, R.J., 2008. Increased pathogenicity against coffee berry borer, Hypothenemus hampei (Coleoptera: Curculionidae) by *Metarhizium anisopliae* expressing the scorpion toxin (AaIT) gene. Journal of Invertebrate Pathology 99, 220-226.

Pedrini, M.R.S., Christian, P., Neilsen, L.K., Reid, S., Chan, L.C.L., 2006. Importance of virus medium interactions on biological activity of wild type Heliothine nucleopolyhedroviruses propogated via suspension insect cell cultures. Journal of Virological Methods 136, 262-272.

Pell, J.K., 2007. Ecological approaches to pest management using entomopathogenic fungi: concepts, theory, practice and opportunities. In: Ekesi, S., Maniania, N.K. (Eds.), Use of Entomopathogenic Fungi in Biological Pest Management. Research Signpost, Kerala, India, pp. 145-177.

Pell, J.K., Hannam, J.J., Steinkraus, D.C., 2010. Conservation biological control using fungal entmopathogens. BioControl 55, 187-198.

Peng, H., Zhou, X. M., Sheng, R.J., 2000. Development of *Dendrolimus punctatus wenshanensis* cytoplasm polyhedrosis virus (Dpw CPV) insecticide. Virilogica Sinica 15, 155-161.

Pereault, R.J., Whalon, M.E., Alston, D.G., 2009. Field efficacy of entomopathogenic fungi and nematodes targeting caged last-instar plum curculio (Coleoptera: Curculionidae) in Michigan cherry and apple orchards. Environmental Entomology 38, 1126-1134.

Perez, E.E., Lewis, E.E., 2004. Suppression of *Meloidogyne incognita* and *Meloidogyne hapla* with entomopathogenic nematodes on greenhouse peanuts and tomatoes. Biological Control 30, 336-341.

Perez, E.E., Lewis, E.E., Shapiro-Ilan, D.I., 2003. Impact of host cadaver on survival and infectivity of entomopathogenic nematodes (Rhabditida: Steinernematidae and Heterorhabditidae) under desiccating conditions. Journal of Invertebrate Pathology 82, 111-118.

Phipps, R.H., Park, J.R., 2002. Environmental benefits of genetically modified crops: global and European perspectives on their ability to reduce pesticide use. Journal of Animal and Feed Sciences 11, 1-18.

Pigott, C.R., Ellar, D.J., 2007. Role of receptors in *Bacillus thuringiensis* crystal toxin activity. Microbiology and Molecular Biology Reviews 71, 255-281.

Pleasants, J.M., Hellmich, R.L., Dively, G.P., Sears, M.K., Stanley-Horn, D.E., Mattila, H.R., Foster, J.E., Clark, T.L., Jones, G.D., 2001. Corn pollen deposition on milkweeds in and near cornfields. Proceedings of the National Academy Sciences USA 98, 11913–11918.

Podgewaite, J. D., 1999. Gypchek a biological insecticide for gypsy moth. Journal of Forestry 97, 16-19.

Poinar, G.O. Jr., 1979. Nematodes for biological contol of insects. CRC Press, Boca Raton, FL. 277 pp.

Poinar, G.O. Jr., 1990. Biology and taxonomy of *Steinernematidae* and *Heterorhabditidae*. In: Gaugler, R., Kaya, H.K. (Eds.), Entomopathogenic Nematodes in Biological Control. CRC Press, Boca Raton, FL, pp. 23-62.

Polavarapu, S., Koppenhöfer, A.M., Barry, J.D., Holdcraft, R.J., Fuzy, E.M., 2007. Entomopathogenic nematodes and neonicotinoids for remedial control of oriental beetle, *Anomala orientalis* (Coleoptera: Scarabaeidae) in highbush blueberry. Crop Protection 26, 1266-1271.

Porcar, M., Gomez, F., Gruppe, A., Gomez-Pajuelo, A., Segura, I., Schroder, R., 2008. Hymenopteran specificity of *Bacillus thuringiensis* strain PS86Q3. Biological Control 45, 427-432.

Poulin, B., 2012. Indirect effects of bioinsecticides on the nontarget fauna: The Camargue experiment calls for future research. Acta Oecologica 44, 28-32.

Poulin, B., Lefebvre, G., Paz, L., 2010. Red flag for green spray: adverse trophic effects of Bti on breeding birds. Journal of Applied Ecology 47, 884–889.

Prater, C.A., Redmond, C.T., Barney, W., Bonning, B.C., Potter, D.A., 2006. Microbial control of black cutworm (Lepidoptera: Noctuidae) in turfgrass using *Agrotis ipsilon* multiple nucleopolyhedrovirus. Journal of Economic Entomology 99, 1129-1137.

Preisser, E.L., Dugaw, C.J., Dennis, B., Strong, D.R., 2005. Long-term survival of the entomopathogenic nematode *Heterorhabditis marelatus*. Environmental Entomology 34, 1501-1506.

Premachandra, W.T.S.D., Borgemeister, C., Berndt, O., Ehlers, R.-U., Poehling, H.-M., 2003. Combined releases of entomopathogenic nematodes and the predatory mite *Hypoaspis aculeifer* to control soil-dwelling stages of the western flower thrips *Frankliniella occidentalis*. BioControl 48, 529-541.

Pszczolkowski, M.A., Brown, J.J., 2004. Enhancement of spinosad toxicity to *Cydia pomonella* neonates by monosodium glutamate receptor agonist. Phytoparasitica 32, 342-350.

Pszczolkowski, M.A., Matos, L., Zah, A., Brown, J.J., 2002. Effect of monosodium glutamate on apple leaf consumption by codling moth larvae. Entomologia Expermentalis et Applicata 103, 91-98.

Qazi, S.S., Khachatourians, G.G., 2007. Hydrated conidia of *Metarhizium anisopliae* release a family of metalloproteases. Journal of Invertebrate Pathology 95, 48-59.

Queseda-Moraga, E., Navas-Cortéz, J.A., Maranhao, E.A., Ortiz-Urquiza, A., Santiago-Álvarez, C., 2007. Factors affecting the occurrence and distribution of entomopathogenic fungi in natural and cultivated soils. Mycological Research 111, 947-966.

Quesada-Moraga, E., Martin-Carballo, I., Garrido-Jurado, I., Santiago-Alvarez, C., 2008. Horizontal transmission of *Metarhizium anisoplae* among laboratory populations of *Ceratitis capitata* (Wiedemann) (Diptera: Tephritidae). Biological Control 47, 115-124.

Queseda-Moraga, E., Muñoz-Ledesma, J., Santiago-Álvarez, C., 2009. Systemic protection of *Papaver somniferum* L. against *Iraella luteipes* (Hymenoptera: Cynipidae) by an endophytic strain of *Beauveria bassiana* (Ascomycota: Hypocreales). Environmental Entomology 38, 723-730.

Quintela, E. D., McCoy, C. W., 1998. Conidial attachment of *Metarhizium anisopliae* and *Beauveria bassiana* to the larval cuticle of *Diaprepes abbreviates* (Coleoptera: Curculionidae) treated with imidacloprid. Journal of Invertebrate Pathology 72, 220-230.

Rabindra R.J. Grzywacz D., 2010. India. In Kabuluk T, Svircev A, Goettel M, Woo S.G.(Eds) Use and Regulation of Microbial Pesticides in Representative Jurisdictions Worldwide' , IOBC Global, pp12-17.

Rahman, M.M., Roberts, H.L., Sarjan, M., Asgari, S., Schmidt, O., 2004. Induction and transmission of *Bacillus thuringiensis* tolerance in the flour moth *Ephestia kuehniella*. Proceedings of the National Academy Sciences USA 101, 2696–2699.

Ram, K., Gruner, D.S., McLaughlin, J.P., Preisser, E., Strong, D.R., 2008. Dynamics of a subterranean cascade in space and time. Journal of Nematology 40, 85-92.

Ramle, M., Wahid, M.B., Norman, K., Glare, T.R., Jackson, T.A., 2005. The incidence and use of *Oryctes* virus for control of rhinoceros beetle in oil palm plantations in Malaysia. Journal of Invertebrate Pathology 89, 89-95.

Ramos- Rodríguez, O., Campbell, J.F., Ramaswamy, S.B., 2006. Pathogenicity of three species of entomopathogenic nematodes to some major stored-product insect pests. Journal of Stored Product Research 42, 241-252.

Ramos-Rodríguez, O., Campbell, J.F., Christen, J.M., Shapiro-Ilan, D.I., Lewis, E.E., Ramaswamy, S.B., 2007. Attraction behavior of three entomopathogenic nematode species towards infected and uninfected hosts. Parasitology 134, 729-738.

Ranjard, L., Poly, F., Lata, J.-C., Mougel, C., Thioulouse, J., Nazaret, S., 2001. Characterization of bacterial and fungal soil communities by automated ribosomal intergenic spacer analysis fingerprints: biological and methodological variability. Applied and Environmental Microbiology 67, 4479-4487.

Rasmann, S., Köllner, T.G., Degenhardt, J., Hiltpold, I., Toepfer, S., Kuhlmann, U., Gershenzon, J., Turlings, T.C.J., 2005. Recruitment of entomopathogenic nematodes by insect-damaged maize roots. Nature 434, 732-737.

Ratanasatien, P., Ketunuti, U., Tantichodok, A., 2005. Positioning of biopesticides in Thailand. In: Côté, J.-C., Otvos, I.S., Schwartz, J.-L., Vincent, C. (Eds.), 6th Pacific Rim Conference on Biotechnology of Bacillus thuringiensis and its Environmental Impact, October 30-November 3, 2005. Victoria, B C, Canada, pp. 100-107.

Ravensberg, W. J., 2011. A Roadmap to the Successful Development and Commercialization of Microbial Pest Control Products for Control of Arthropods. Springer, Dordrecht, The Netherlands. 383 pp.

Reay, S.D., Brownbridge, M., Cummings, N.J., Nelson, T.L., Souffre, B., Lignon, C., Glare, T.R., 2008. Isolation and characterization of *Beauveria* spp. associated with exotic bark beetles in New Zealand *Pinus radiata* plantation forests. Biological Control 46, 484-494.

Reid, S., Chan, L. Van Oers, M. 2014, Production of entomopathogenic viruses. In Juan A. Morales-Ramos, M. Guadalupe Rojas, and David, I. Shapiro-Ilan (Eds) Mass Production of Beneficial Organisms, Elsevier, Amsterdam. pp 437- 482.

Rehner, S.A., Buckley, E.P., 2003. Isolation and characterization of microsatellite loci from the entomopathogenic fungus *Beauveria bassiana* (Ascomycota: Hypocreales). Molecular Ecology Notes 3, 409-411.

Rehner, S.A., Buckley, E.P., 2005. A *Beauveria* phylogeny inferred from nuclear ITS and EF1-alpha sequences: evidence for cryptic diversification and links to *Cordyceps* teleomorphs. Mycologia 97, 84-98.

Rehner, S.A., Posada, F., Buckley, E.P., Infante, F., Castillo, A., Vega, F.E., 2006. Phylogenetic origins of African and Neotropical *Beauveria bassiana s.l.* pathogens of the coffee berry borer, *Hypothenemus hamperi*. Journal of Invertebrate Pathology 93, 11-21.

Reis-Menini, C.M.R., Prata, M.C.A., 2008. Compatibility between the entomopathogenic nematode *Steinernema glaseri* and an acaricide in the control of *Rhipicephalus* (*Boophilus*) *microplus* (Acari: Ixodidae). Parasitology Research 103, 1391-1396.

Ricroch, A., Berge, J.B., Kuntz M., 2010. Is the German suspension of MON810 maize cultivation scientifically justified? Transgenic Research 19, 1-12.

Riga, K., Lacey, L. A., Guerra, N., Headrick, H. L., 2006. Control of the oriental fruit moth, *Grapholita molesta*, using entomopathogenic nematodes in laboratory and bin assays. Journal of Nematology 38, 168-171.

Roberts, D.W., St. Leger, R.J., 2004. *Metarhizium* spp., cosmopolitan insect-pathogenic fungi: Mycological aspects. Advances in Applied Microbiology 54, 1-70.

Roh, J.Y., Choi, J.Y., Li, M.S., Jin, B.R., Je, Y.H., 2007. *Bacillus thuringiensis* as a specific, safe, and effective tool for insect pest control. Journal of Microbiology and Biotechnology 17, 547-559.

Rohner-Thielen, E., 2005. Organic Farming in Europe, Statistics in Focus: Agriculture and Fisheries, Statistical Office of the European Communities (Eurostat), http://www.scribd.com/doc/2364917/Organic-Farming-in-Europe-ROHNERTHIELEN-2005. Accessed April 29, 2010.

Rohles, M., Churchill, A.C.L., 2011. Fungal secondary metabolites as modulators of interactions with insects and other arthropods. Fungal Genetics Biology 48, 23-34.

Romeis, J., Meissle, M., Bigler F., 2006. Transgenic crops expressing *Bacillus thuringiensis* toxins and biological control. Nature Biotechnology 24, 63-71.

de la Rosa, W., Alatorre, R., Barrera, J. F. Toriello, C., 2000. Effect of *Beauveria bassiana* and *Metarhizium anisopliae* (Deuteromycetes) upon the coffee berry borer (Coleoptera: Scolytidae) under field conditions. Journal of Economic Entomology 93, 1409-1414.

Rowley, D. L., Popham, H. J. R., Harrison, R. L., 2011. Genetic variation and virulence of nucleopolyhedroviruses isolated worldwide from the heliothine pests *Helicoverpa armigera*, *Helicoverpa zea*, and *Heliothis virescens*. Journal of Invertebrate Pathology 107, 112-126.

Roy, H.E., Baverstock, J., Pell, J.K., 2007. Manipulating behaviour: a strategy for pest control? In: Ekesi, S., Maniania, N.K. (Eds.), Use of Entomopathogenic Fungi in Biological Pest Management. Research Signpost, Kerala, India, pp. 179-196.

Roy, H.E., Brodie, E.L., Chandler, D., Goettel, M., Pell, J., Wajnberg, E., Vega, F., 2010a. Hidden depths: Understanding the evolution and ecology of fungal entomopathogens. BioControl 55, 1-6.

Roy, H.E., Vega, F.E., Chandler, D., Goettel, M.S., Pell, J.K., Wajnberg, E. (Eds.) 2010b. The Ecology of Fungal Entomopathogens. Springer, Dordecht,. 198 pp.

Ryder, J.J., Griffin, C.T., 2003. Phased infectivity in *Heterorhabditis megidis*: the effects of infection density in the parental host and filial generation. International Journal of Parasitology 33, 1013-1018.

St. Leger, R.J., 2008. Studies on adaptations of *Metarhizium anisopliae* to life in the soil. Journal of Invertebrate Pathology 98, 271-276.

St. Leger, R.J., Wang, C., Fang, W., 2011. New perspectives on insect pathogens. Fungal Biology Reviews 25, 84-88.

Sajap, A.S., Bakir, M.A., Kadir, H.A., Samad, N.A., 2009. Efficacy of selected adjuvants for protecting Spodoptera litura nucleopolyhedrovirus from sunlight inactivation. Journal of Asia-Pacific Entomology 12, 85–88.

San-Blas, E., Gowen, S.R., 2008. Facultative scavenging as a survival strategy of entomopathogenic nematodes. International Journal of Parasitology 38, 85–91.

Sandhu, S.K., Jagdale, G.B., Hogenhout, S.A., Grewal, P.S., 2006. Comparative analysis of the expressed genome of the infective juvenile entomopathogenic nematode, *Heterorhabditis bacteriophora*. Molecular and Biochemical Parasitology 145, 239-244.

Sauphanor, B., Berling, M., Toubon, J.F., Reyes, M., Delnatte, J., 2006. Carpocapse des pommes: cas de résistance aux virus de la granulose dans le Sud-Est. Phytoma 590, 24-27.

Saxena, D., Stotsky, G., 2001. *Bacillus thuringiensis* (Bt) toxin released from root exudates and biomass of Bt corn has no apparent effect on earthworms, nematodes, protozoa, bacteria, and fungi in soil. Soil Biology and Biochemistry 33, 1225-1230.

Scheepmaker, J.W.A., Butt, T.M., 2010. Natural and released inoculum levels of entomopathogenic fungal biocontrol agents in soil in relation to risk assessment and in accordance with EU regulations. Biocontrol Science and Technology 20, 503-552.

Schmidt, S., Tomasi, C., Pasqualini, E., Ioriatti, C., 2008. The biological efficacy of pear ester on the activity of granulosis virus for codling moth. Journal of Pest Science 81, 29-34.

Schmitz T G. Schmitz A and Moss C B. 2005. Economic impact of starlink corn. Agribusiness 21: 91–407.

Schnepf, E., Crickmore, N., Van Rie, J., Lereclus, D., Baum, J.. Feitelson, J., Zeigler, D. R., Dean, D. H., 1998. *Bacillus thuringiensis* and its pesticidal crystal proteins. Microbiology and Molecular Biology Reviews 62, 775-806.

Scholte, E.-J., Knols, B.G., Takken, W., 2004. Autodissemination of the entomopathogenic fungus *Metarhizium anisopliae* amongst adults of the malaria vector *Anopheles gambiae s.s.* Malaria Journal 3, 45.

Scholte, E.-J., Nijiru, B.N., Smallegang, R.C., Takken, W., Knols, B.G., 2003. Infection of malaria (*Anopheles gambiae s.s.*) and filariasis (*Culex quinquefasciatus*) vectors with the entomopathogenic fungus *Metarhizium anisopliae*. Malaria Journal 2, 29.

Scholte, E.-J., Ng'habi, K., Kihonda, J., Takken, W., Paaijmans, K., Abdulla, S., Killeen, G.F., Knols, B.G.J., 2005. An entomopathogenic fungus for control of adult African malaria mosquitoes. Science 308, 1641-1643.

Schroer, S., Ehlers, R.-U., 2005. Foliar application of the entomopathogenic nematode *Steinernema carpocapsae* for biological control of diamondback moth larvae (*Plutella xylostella*). Biological Control 33, 81-86.

Schroer, S., Sulistyanto, D., Ehlers, R.-U., 2005. Control of *Plutella xylostella* using polymer-formulated *Steinernema carpocapsae* and *Bacillus thuringiensis* in cabbage fields. Journal of Applied Entomology 129, 198-204.

Schwartz, J.-L., Potvin, L., Coux, F., Charles, J.-F., Berry, C., Humphreys, M.J., Jones, A.F., Bernhart, I., Dalla Serra, M., Menestrina, G., 2001. Permeabilization of model lipid membranes by *Bacillus sphaericus* mosquitocidal binary toxin and its individual components. Journal of Membrane Biology 184, 171-183.

Schwartz, H.T., Antoshechkin, I., Sternberg, P.W., 2011. Applications of high-throughput sequencing to symbiotic nematodes of the genus *Heterorhabditis*. 55, 111–118.

Schwarzenbach, K., Enkerli, J., Widmer, F., 2007a. Objective criteria to assess representativity of soil fungal community profiles. Journal of Microbiological Methods 68, 358-366.

Schwarzenbach, K., Widmer, F., Enkerli, J., 2007b. Cultivation-independant analysis of fungal genotypes in soil by using simple sequence repeat markers. Applied and Environmental Microbiology 73, 6519-6525.

Sears, M.K., Hellmich, R.L., Stanley-Horn, D.E., Oberhauser, K.S., Pleasants, J.M., Mattila, H.R., Siegfried, B.D., Dively, G.P., 2001. Impact of Bt corn pollen on monarch butterfly populations: a risk assessment. Proceedings of the National Academy Sciences USA 98, 11937–11942.

Shah, P. A., Pell, J.K., 2003. Entomopathogenic fungi as biological control agents. Applied Microbiology and Biotechnology 61, 413-423.

Shah, P.A., Pell, J.K., 2003. Entomopathogenic fungi as biological control agents. Applied Microbiolologyand Biotechnology 61, 413-423.

Shah, F., Butt, T.M., 2005. Influence of nutrition on the production and physiology of sectors produced by the insect pathogenic fungus *Metarhizium anisopliae*. FEMS Microbiology Letters 250, 201-207.

Shah, F., Wang, C.S., Butt, T.M., 2005. Nutrition influences growth and virulence of the insect-pathogenic fungus *Metarhizium anisopliae*. FEMS Microbiology Letters 251, 259-266.

Shah, F.A., Ansari, M.A., Prasad, M., Butt, T.M., 2007. Evaluation of black vine weevil (*Otiorhynchus sulcatus*) control strategies using *Metarhizium anisopliae* with sublethal doses of insecticides in disparate horticultural growing media. Biological Control 40, 246-252.

Shah, F.A., Gaffney, M., Ansari, M.A., Prasad, M., Butt, T.M., 2008. Neem seed cake enhances the efficacy of the insect pathogenic fungus *Metarhizium anisopliae* for the control of black vine weevil, *Otiorhynchus sulcatus* (Coleoptera: Curculionidae). Biological Control 44, 111-115.

Shah, F.A., Greig, C., Hutwimmer, S., Strasser, H., Dyson, P., Carlile, B., Butt, T.M., 2009. Evaluation of the effects of the insect pathogenic fungus *Metarhizium anisopliae* on microbial populations of disparate plant growing media. Fungal Ecology 3, 185–194.

Shapiro-Ilan, D.I., Brown, I., 2013. Earthworms as phoretic hosts for *Steinernema carpocapsae* and *Beauveria bassiana*: Implications for enhanced biological control. Biological Control 66, 41-48.

Shapiro-Ilan D.I., Gaugler, R., 2002. Production technology for entomopathogenic nematodes and their bacterial symbionts. Journal of Industrial Microbiology and Biotechnology 28,137-146.

Shapiro-Ilan, D. I., Grewal, P.S., 2008. Entomopathogenic nematodes and insect management. In: Capinera, J.L. (Ed.), Encyclopedia of Entomology, 2nd Edition. Springer, Dordrecht, The Netherlands, pp. 1336-1340.

Shapiro-Ilan, D.I., Lewis, E.E., Behle, R.W., McGuire, M.R., 2001. Formulation of entomopathogenic nematode-infected-cadavers. Journal of Invertebrate Pathology 78, 17-23.

Shapiro-Ilan, D.I., Gouge, D.H., Koppenhöfer, A.M., 2002a. Factors affecting commercial success: case studies in cotton, turf and citrus. In: Gaugler, R. (Ed.), Entomopathogenic Nematology. CABI, Wallingford, UK, pp 333-356.

Shapiro-Ilan, D.I., Gaugler, R., Tedders, W.L., Brown, I., Lewis, E.E., 2002b. Optimization of inoculation for in vivo production of entomopathogenic nematodes. Journal of Nematology 34, 343-350.

Shapiro-Ilan, D.I., Gardner, W., Fuxa, J.R., Wood, B.W., Nguyen, K., Adams, B.J., Humber, R.A., Hall, M.J. 2003a. Survey of entomopathogenic nematodes and fungi endemic to pecan orchards of the southeastern US and their virulence to the pecan weevil (Coleoptera: Curculionidae). Environmental Entomology. 32: 187-195.

Shapiro-Ilan, D.I., Lewis, E.E., Tedders, W.L., Son, Y., 2003b. Superior efficacy observed in entomopathogenic nematodes applied in infected-host cadavers compared with application in aqueous suspension. Journal of Invertebrate Pathology 83, 270-272.

Shapiro-Ilan, D.I, Mizell, R.F., Cottrell, T.E., Horton, D.L., 2004a. Measuring field efficacy of *Steinernema feltiae* and *Steinernema riobrave* for suppression of plum curculio, *Conotrachelus nenuphar*, larvae. Biological Control 30, 496-503.

Shapiro-Ilan, D.I., Jackson, M., Reilly, C.C., Hotchkiss, M.W., 2004b. Effects of combining an entomopathogenic fungi or bacterium with entomopathogenic nematodes on mortality of *Curculio caryae* (Coleoptera: Curculionidae). Biological Control 30, 119-126.

Shapiro-Ilan, D.I., Stuart, R.J., McCoy, C.W., 2005. Targeted improvement of *Steinernema carpocapsae* for control of the pecan weevil, *Curculio caryae* (Horn) (Coleoptera: Curculionidae) through hybridization and bacterial transfer. Biological Control 34, 215-221.

Shapiro-Ilan, D.I., Gouge, G.H., Piggott, S.J., Patterson Fife, J., 2006a. Application technology and environmental considerations for use of entomopathogenic nematodes in biological control. Biological Control 38, 124-133.

Shapiro-Ilan, D.I., Cottrell, T.E., Brown, I., Gardner, W.A., Hubbard, R.K., Wood, B.W., 2006b. Effect of soil moisture and a surfactant on entomopathogenic nematode suppression of the pecan weevil, *Curculio caryae*. Journal of Nematology 38, 474–482.

Shapiro-Ilan, D.I., Nyczepir, A.P., Lewis, E.E., 2006c. Entomopathogenic nematodes and bacteria applications for control of the pecan root-knot nematode, *Meloidogyne partityla,* in the greenhouse. Journal of Nematology 38, 449–454.

Shapiro-Ilan, D.I., Lacey, L.A., Siegel, J.P., 2007. Microbial control of insect pests of stone fruit and nut crops. In: Lacey, L.A., Kaya, H. K. (Eds.), Field Manual of Techniques in Invertebrate Pathology: Application and Evaluation of Pathogens for Control of Insects and Other Invertebrate Pests, 2nd Edition. Springer, Dordrecht, The Netherlands, pp. 547-565.

Shapiro-Ilan, D.I., Mizell, R.F. III, Cottrell, T.E., Horton, D.L., 2008a. Control of plum curculio, *Conotrachelus nenuphar* with entomopathogenic nematodes: effects of application timing, alternate host plant, and nematode strain. Biological Control 44, 207-215.

Shapiro-Ilan, D.I., Guadalupe Rojas, M., Morales-Ramos, J.A., Lewis, E.E., Tedders, W.L., 2008b. Effects of host nutrition on virulence and fitness of entomopathogenic nematodes: lipid and protein based supplements in *Tenebrio molitor* diets. Journal of Nematology 40, 13-19.

Shapiro-Ilan, D.I., Tedders, W.L., Lewis, E.E., 2008c. US Patent 7,374,773. Application of entomopathogenic nematode-infected cadavers from hard-bodied arthropods for insect suppression.

Shapiro-Ilan, D.I., Cottrell, T.E., Mizell, R.F. III, Horton, D.L., Davis, J., 2009a. A novel approach to biological control with entomopathogenic nematodes: prophylactic control of the peachtree borer, *Synanthedon exitiosa*. Biological Control 48, 259-263.

Shapiro-Ilan, D.I., Reilly, C.C, Hotchkiss, M.W., 2009b. Suppressive effects of metabolites from *Photorhabdus* and *Xenorhabdus* spp. on phytopathogens of peach and pecan. Archives of Phytopathology and Plant Protection 42, 715–728.

Shapiro-Ilan, D.I., Campbell, J.F., Lewis, E.E., Elkon, J.M., Kim-Shapiro, D.B., 2009c. Directional movement of parasitic nematodes in response to electrical current. Journal of Invertebrate Pathology 100, 134–137.

Shapiro-Ilan, D.I., Morales-Ramos, J.A., Rojas, M.G., Tedders, W.L., 2010a. Effects of a novel entomopathogenic nematode–infected host formulation on cadaver integrity, nematode yield, and suppression of *Diaprepes abbreviatus* and *Aethina tumida* under controlled conditions. Journal of Invertebrate Pathololology 103, 103–108.

Shapiro-Ilan, D. I., Cottrell, T. E., Mizell, R. F. III, Horton, D. L, Behle, B., Dunlap, C., 2010b. Efficacy of *Steinernema carpocapsae* for control of the lesser peachtree borer, *Synanthedon pictipes*: improved aboveground suppression with a novel gel application. Biological Control.54, 23–28.

Shapiro-Ilan, D.I., Campbell, J.F., Lewis, E.E., Kim-Shapiro, D.B., 2012a. Directional movement of entomopathogenic nematodes in response to electrical field: Effects of species, magnitude of voltage, and infective juvenile age. Journal of Invertebrate Pathology 109, 34-40.

Shapiro-Ilan, D.I., Bruck, D.J., Lacey, L.A., 2012b. Principles of epizootiology and microbial control. In: Vega, F.E., Kaya, H.K. (Eds.), Insect Pathology, 2nd Edition. Academic Press, San Diego. pp. 29-72.

Shapiro-Ilan, D.I., Wright, S.E., Tuttle, A.F., Cooley, D.R., Leskey, T.C., 2013. Using entomopathogenic nematodes for biological control of plum curculio, *Conotrachelus* *nenuphar*: Effects of irrigation and species in apple orchards. Biological Control 67, 123-129.

Shapiro-Ilan, D.I., Han, R., Qiu, X., 2014a. Production of entomopathogenic nematodes. In: Morales-Ramos, J.A., Rojas, M.G., Shapiro-Ilan, D.I., (Eds.), Mass Production of Beneficial Organisms: Invertebrates and Entomopathogens, Academic Press, Amsterdam, pp. 321-356.

Shapiro-Ilan, D.I., Lewis, E.E., Schliekelman, P., 2014b. Aggregative group behavior in insect parasitic nematode dispersal. International Journal of Parasitology 44, 49-54.

Shapiro, M., El-Salamouny, S., Shepard, B.M., 2008. Green tea extracts as ultraviolet protectants for the beet armyworm, *Spodoptera exigua*, nucleopolyhedrovirus. Biocontrol Science and Technology 18, 591-603.

Shelton A. M., 2012. Genetically engineered vegetables expressing proteins from *Bacillus thuringiensis* for insect; resistance successes, disappointments, challenges and ways to move forward. GM Crops and Food: Biotechnology in Agriculture and the Food Chain 3, 1-9

Shelton, A.M., Zhao, J.-Z., Roush R.T., 2002. Economic, ecological, food safety, and social consequences of the deployment of BT transgenic plants. Annual Review of Entomology 47, 845-881.

Shelton, A., Wang, P., Zhao, J.-Z., Roush, R.T., 2007. Resistance to insect pathogens and strategies to manage resistance: an update. In: Lacey, L.A., Kaya, H.K. (Eds.), Field Manual of Techniques in Invertebrate Pathology: Application and Evaluation of Pathogens for Control of Insects and Other Invertebrate Pests, 2nd Edition. Springer, Dordrecht, The Netherlands. pp. 793-718.

Shimazu, M., Sato, H., Machara, N., 2002. Density of the entomopathogenic fungus, *Beauveria bassiana* Vuillemin (Deuteromycotina: Hyphomycetes) in forest air and soil. Applied Entomology and Zoology 37, 19-26.

Siegel, J.P., Lacey, L.A., Higbee, B.S., Noble, P., Fritts, R. Jr., 2006. Effect of application rates and abiotic factors on *Steinernema carpocapsae* for control of overwintering navel orangeworm (Lepidoptera: Pyralidae, *Amyelois transitella*) in pistachios. Biological Control 36, 324-330.

Singh, S., Moore, S., Spillings, S., Hendry, D., 2003. South African isolate of *Cryptophlebia leucotreta* granulovirus. Journal Invertebrate Pathology 83, 249-252.

Singhal, V., 2004. Biopesticides in India. In: Kaushik, N. (Ed.), Biopesticides for Sustainable Agriculture, Prospects and Constraints. TERI Press, Delhi, India, pp. 31-39.

Skadsen, R., Hohn, T., 2004. Use of *Fusarium graminearum* transformed with *gfp* to follow infetion patterns in barley and *Arabidopsis*. Physiological and Molecular Plant Pathology 64, 45-53.

Skovmand, O., 2007. Microbial control in Southeast Asia. Journal of Invertebrate pathology 95, 164-174.

Skovmand, O., Kerwin, J., Lacey, L.A., 2007. Microbial control of mosquitoes and black flies. In: Lacey, L.A., Kaya, H. K. (Eds.), Field Manual of Techniques in Invertebrate Pathology: Application and Evaluation of Pathogens for Control of Insects and Other Invertebrate Pests, 2nd Edition. Springer, Dordrecht, The Netherlands, pp. 735-750.

Slavicek J.M., 2012. Baculovirus enhancins and their role in viral pathogenicity. In: Adoga, M, P. Ed.) Molecular Virology, Intech. Rijecka. 147-155.

Solter, L.F., Hajek, A.E., 2009. Control of gypsy moth, *Lymantria dispar*, in North America since 1878. In: Hajek, A.E., Glare, T.R., O'Callaghan, M. (Eds.), Use of Arthropods for Control and Eradication of Invasive Arthropods. Springer BV, Netherlands, pp. 181-212.

Somasekhar, N., Grewal, P.S., De Nardo, E.A., Stinner, B.R., 2002. Non-target effects of entomopathogenic nematodes on the soil nematode community. Journal of Applied Ecology 39, 735-744.

Somvanshi, V.S., Koltai, H., Glazer, I., 2008. Expression of different desiccation-tolerant genes in various species of entomopathogenic nematodes. Molecular and Biochemical Parasitology 158, 65-71.

Sosa-Gómez, D.R., Moscardi, F., Santos, B., Alves, L.F.A., Alves, S.B., 2008. Produção e uso de virus para o controle de pragas na América Latina. In: Alves, S.B., Lopes, R.B. (Eds.), Controle Micobiano de Pragas na América Latina: avanços e desafios. Fundação de Estudos Agrários Luiz de Queiroz, Piracicaba, Brasil, pp. 49-68.

Spiridonov, S.E., Moens, M., Wilson, M.J., 2007. Fine scale spatial distributions of two entomopathogenic nematodes in a grassland soil. Applied Soil Ecology 37, 192-201.

Sporleder, M., 2003. The granulovirus of the potato tuber moth *Phthorimaea operculella* (Zeller): characterization and prospects for effective mass production and pest control. In: Kroschel, J. (Ed.), Advances in Crop Research (Vol. 3). Margraf Verlag, Weikersheim, Germany, p. 196.

Sporleder, M., Kroschel, J., 2008. The potato tuber moth granulovirus (*Po*GV): use, limitations and possibilities for field applications. In: Kroschel, J., Lacey, L.A. (Eds.), Integrated Pest Management for the Potato Tuber Moth, *Phthorimaea operculella* (Zeller)–a Potato Pest of

Global Importance. Tropical Agriculture 20, Advances in Crop Research 10. Margraf Publishers, Weikersheim, Germany, pp. 49-71.

Sporleder, M., Lacey, L.A., 2013. Biopesticides. In: Giordanengo, P., Vincent, C., Alyokhin, A. (Eds.), Insect Pests of Potato: Global Perspectives on Biology and Management. Academic Press, Amsterdam. pp. 463-497.

Sporleder, M., Zegarra, O., Maritza, E., Cauti, R., Kroschel, J., 2008. Effects of temperature on the activity and kinetics of the granulovirus infecting the potato tuber moth *Phthorimaea operculella* Zeller (Lepidoptera: Gelechiidae). Biological Control 44, 286-295.

Stanley-Horn, D.E., Dively, G.P., Hellmich, R.L., Mattila, H., Sears, M.K., Rose, R., Jesse, L.C., Losey, J.E., Obrycki, J.J., Lewis, L., 2001. Assessing the impact of Cry1Ab-expressing corn pollen on monarch butterfly larvae in field studies. Proceedings of the National Academy Sciences USA 98, 11931–11936.

Steinkraus, D.C., 2006. Factors affecting transmission of fungal pathogens of aphids. Journal of Invertebrate Pathology 92, 125-131.

Steinkraus, D.C., 2007a. Management of aphid populations in cotton through conservation: delaying insecticide spraying has its benefits. In: Vincent, C., Goettel, M.S., Lazarovits, G. (Eds.), Biological Control: A Global Perspective. CAB International, Wallingford, UK, pp 383-391.

Steinkraus, D.C., 2007b. Documentation of naturally occurring pathogens and their impact in agroecosystems. In: Lacey, L.A., Kaya, H.K. (Eds.), Field Manual of Techniques in Invertebrate Pathology: Application and Evaluation of Pathogens for Control of Insects and Other Invertebrate Pests, 2nd Edition. Springer, Dordrecht, The Netherlands, pp. 267-281.

Steinkraus, D.C., Boys, G.O., Rosenheim, J.A., 2002. Classical biological control of *Aphis gossypii* (Homoptera: Aphididae) with *Neozygites fresnii* (Entomophthorales: Neozygitaceae) in California cotton. Biological Control 25, 297-304.

Stevenson, P.C., D'Cunha, R.F., Grzywacz, D., 2010. Inactivation of baculovirus by the isoflavenoids on chickpea (Cicer arietinum) leaf surfaces reduces the efficacy of Nucleopolyhedrovirus against Helicoverpa armigera. Journal of Chemical Ecology 36, 227-235.

Stock, S.P., Koppenhöfer, A.M., 2003. *Steinernema scarabaei* n. sp. (Rhabditida: Steinernematidae), a natural pathogen of scarab beetle larvae (Coleoptera: Scarabaeidae) from New Jersey, USA. Nematology 5, 191-204.

Stock, S.P., Hunt, D.J., 2005. Morphology and systematics of nematodes used in biocontrol. In: Grewal, P.S., Ehlers, R.-U., Shapiro-Ilan, D.I. (Eds.), Nematodes as Biocontrol Agents. CABI, Wallingford, UK, pp. 3-43.

Storer, N.P., Thompson, G.D., Head, G.P., 2012. Application of pyramided traits against Lepidoptera in insect resistance management for Bt crops. GM Crops Food. 3,154-162.

Strauch, O., Oestergaard, J., Hollmer, S., Ehlers, R.-U., 2004. Genetic improvement of the desiccation tolerance of the entomopathogenic nematode *Heterorhabditis bacteriophora* through selective breeding. Biological Control 31, 218-226.

Stuart, R.J., Shapiro-Ilan, D.I., James, R.R., Nguyen, K.B., McCoy, C.W., 2004. Virulence of new and mixed strains of the entomopathogenic nematode *Steinernema riobrave* to larvae of the citrus root weevil *Diaprepes abbreviatus*. Biological Control 30, 439-445.

Stuart, R.J., El-Borai, F.E., Duncan, L.W., 2008. From augmentation to conservation of entomopathogenic nematodes: trophic cascades, habitat manipulation and enhanced biological control of *Diaprepes abbreviatus* root weevils in Florida citrus groves. Journal of Nematology 40, 73-84.

Sundh, I. Goettel, M.S. 2013. Regulating biocontrol agents: A historical perspective and a critical examination comparing microbial and macrobial agents**.** BioControl 58, 575-593.

Sundh, I., A. Wilcks and M.S. Goettel. 2012a**.** Microbes and the law – Safety assessment and regulation of beneficial microorganisms**.** In: Sundh, I., Wilcks, A., Goettel, M.S. (Eds). Beneficial Microorganisms in Agriculture, Food and the Environment. CABI international, Wallingford, UK. pp. 1-11.

Sundh, I., Wilcks, A., Goettel, M.S. (Eds). 2012b. Beneficial Microorganisms in Agriculture, Food and the Environment. Safety Assessment and Regulation. CABI international, Wallingford, UK. 343 pp.

Sun, X., Peng, H., 2007. Recent advances in control of insect pests by using viruses in China. Virologica Sinica 22, 158-162.

Sung, G.-H., Spatafora, J.W., Zare, R., Hodge, K.T., Gams, W., 2001. A revision of *Verticillium* sect. *Prostrata.* II. Phylogenetic analyses of SSU and LSU nuclear rDNA sequences from anamorphs and teleomorphs of the *Clavicipitaceae.* Nova Hedwigia 72, 311–328.

Sung, G.-H., Hywel-Jones, N.L., Sung, J.M., Luangsa-ard, J.J., Shrestha, B., Spatafora, J.W., 2007. Phylogenetic classification of *Cordyceps* and the clavicipitaceous fungi. Studies in Mycology 57, 5-59.

Suzuki, N., Hori, H., Ogiwara, K., Asano, S., Sato, R., Ohba, M., Iwahana, H., 1992. Insecticidal spectrum of a novel isolate of *Bacillus thuringiensis* serovar *japonensis*. Biological Control 2, 138-142.

Szewcyk, B., Hoyos-Carvajal, L., Paluszek, M., Skrzecz, I., Lobo de Souza, M., 2006. Baculoviruses re-emerging biopesticides. Biotechnology Advances 24 143-160.

Tabashnik, B. E., 1994. Evolution of resistance to *Bacillus thuringiensis*. Annual Review of Entomology 39, 47-79.

Tabashnik, B.E., 2008. Delaying insect resistance to transgenic crops. Proceedings of the National Academy of Sciences USA 105, 19029-19030.

Tabashnik, B. E., Finson, N., Johnson, M. W., Moar, W. J., 1993. Resistance to toxins from *Bacillus thuringiensis* subsp. *kurstaki* causes minimal cross-resistance to *B. thuringiensis* subsp. *aizawa*i in the diamondback moth (Lepidoptera: Plutellidae). Applied and Environmental Microbiology, 59, 1332-1335.

Tabashnik, B.E., Gassman, A.J., Crowder, D.W., Carriere, Y., 2008a. Field-evolved resistance to Bt toxins. Nature 26, 1074-1076.

Tabashnik, B.E., Gassmann, A.J., Crowder, D.W., Carrière, Y., 2008b. Insect resistance to Bt crops: evidence versus theory. Nature Biotechnology 26, 199-202.

Tabashnik, B.E., Van Rensburg, J.B., Carrière, Y., 2009. Field-evolved insect resistance to Bt crops: definition, theory, and data. Journal of Economic Entomology 102, 2011-2025.

Tabashnik, B.E, Brévault T., Carrière, Y., 2013. Insect resistance to Bt crops: lessons from the first billion acres. Nature Biotechnology 31, 510–521.

Tamez-Guerra, P., McGuire, M.R., Behle, R.W., Hamm, J.J., Sumner, H.R., Shasha, B.S., 2000. Sunlight persistence and rainfastness of spray-dried formulations of baculoviru, isolated from *Anagrapha falcifera* (Lepidoptera: Noctuidae). Journal of Economic Entomology 93, 210-218.

Tamez-Guerra, P., McGuire, M.R., Behle, R.W., Shasha, B.S., Pingel, R.L., 2002. Storage stability of *Anagrapha falcifera* nucleopolyhedrovirus in spray-dried formulations. Journal of Invertebrate Pathology 79, 7-16.

Tanada, Y., 1964. A granulosis virus of the codling moth, *Carpocapsae pomonella* (Linnaeus) (Olethreutidae, Lepidoptera). Journal Insect Pathology 6, 378-380.

Tarocco, F., Lecuona, R.E., Couto, A.S., Arcas, J.A., 2005. Optimization of erythritol and glycerol accumulation in conidia of *Beauveria bassiana* by solid state fermentation, using response surface methodology. Applied Microbiology and Biotechnology 68, 481-488.

Teulon, D.A.J., Davidson, M.M., Hedderly, D.I., James, D.E., Fletcher, C.D., Larsen, L., Green, V.C., Perry, N.B, 2007a. 4-Pyridyl carbonyl and related compounds as thrips lures: Effectiveness for onion thrips and New Zealand flower thrips in field experiments. Journal of Agriculture and Food Chemistry 55, 6198-6205.

Teulon, D.A.J., Butler, R.C., James, D.E., Davidson, M.M., 2007b. Odour-baited traps influence thrips capture in proximal unbaited traps in the field. Entomologis Experimentalis et Applicata 123, 253-262.

Thakre, M., Thakur, M., Malik, N., Ganger, S., 2011. Mass scale cultivation of entomopathogenic fungus *Nomuraea rileyi* using agricultural products and agro wastes. Journal of Biopesticides 4, 176-179.

Thaochan, N., Ngampongsai, A. 2015. Effects of autodisseminated *Metarhizium guizhouense* PSUM02 on mating propensity and mating competitiveness of *Bactrocera curcubitae* (Diptera: Tephritidae). Biocontrol Science and Technology 25, (In Press).

Thakore, Y., 2006. The biopesticides market for global agricultural use. Industrial Biotechnology 2, 194-208.

Theilmann, D.A., Blissard, G.W., Bonning, B., Jehle, J., O'Reilly, D.R., Rohrmann, G.F., Theim, S., Vlak, J., 2005. Family baculoviridae. In: Fauquet, C.M., Mayo, M.A., Maniloff, M., Desselberger, U., Ball, L.A. (Eds.), Virus Taxonomy, Eighth Report of the International Committee on Virus Taxonomy. Elsevier Press, San Diego, pp. 177-185.

Thomas, M.B., 2000. Development of a mycoinsecticide for biological control of locusts in Southern Africa. In: R.A. Cheke, L.J. Rosenberg, Kieser, M.E. (eds.) Research Priorities for Migrant Pests of Agriculture in Southern Africa. Proceedings of a DFID/NRI/ARC-PPRI workshop, Pretoria, South Africa, 24-26 March 1999. Natural Resources Institute, Chatham, UK, pp. 173-182.

Thompson, S.R., Brandenburg, R.L., 2005. Tunneling responses of mole crickets (Orthoptera: Gryllotalpidae) to the entomopathogenic fungus, *Beauveria bassiana*. Environmental Entomology 34, 140-147.

Thornström, C-G., 2012. International conventions and agreements – consequences for international trade and utilization of biological matter, including microorganisms. In: Sundh, I., Wilcks, A., Goettel, M.S. (Eds). Beneficial Microorganisms in Agriculture, Food and the Environment. CABI international, Wallingford, UK. pp 293-307.

Tirado, R., 2010. Picking Cotton agriculture; the choice between organic and genetically-engineered cotton for farmers in South India Greenpeace Research Laboratories Technical Note 03/2010 http://www.greenpeace.org/international/Global/international/publications/agriculture/2010/Picking_Cotton.pdf

Toepfer, S., Peters, A., Ehlers, R.-U., Kuhlmann, U., 2008. Comparative assessment of the efficacy of entomopathogenic nematode species at reducing western corn rootworm larvae and root damage in maize. Journal of Applied Entomology 132, 337-348.

Toprak, U., Susurluk, H., Gurkan, M.O., 2007. Viral-enhancing activity of an optical brightener for *Spodoptera littoralis* (Lepidoptera: Noctuidae) nucleopolyhedrovirus. Biocontrol Science and Technology 17, 423-431.

Torr, P., Heritage, S., Wilson, M.J., 2004. Vibrations as a novel signal for host location by parasitic nematodes. International Journal of Parasitology 34, 997-999.

Torzilli, A.P., Sikaroodi, M., Chalkley, D., Gillevet, P.M., 2006. A comparison of fungal communities from four salt marsh plants using automated ribosomal intergenic spacer analysis. Mycologia 98, 690-698.

Townsend, R.J., O'Callaghan, M., Johnson, V.W., Jackson, T.A., 2003. Compatibility of microbial control agents *Serratia entomophila* and *Beauveria bassiana* with selected fertilisers. New Zealand Plant Protection 56, 118-122.

Townsend, R. J., Nelson, T. L., Jackson, T. A., 2010. *Beauveria brongniartii* – a potential biocontrol agent for use against manuka beetle larvae damaging dairy pastures on Cape Foulwind. New Zealand Plant Protection 63, 224-228.

Traugott, M., Weissteiner, S., Strasser, H., 2005. Effects of the entomopathogenic fungus *Beauveria brongniartii* on the non-target predator *Poecilus versicolor* (Coleoptera: Carabidae). Biological Control 33, 107-112.

Tsao, R., Marvin, C.H., Broadbent, A.B., Friesen, M., Allen, W.R., McGarvey, B.D., 2005. Evidence for an isobutylamide associated with host-plant resistance to western flower thrips, *Frankliniella occidentalis*, in chrysanthemum. Journal of Chemical Ecology 31, 103-110.

Tschenn, J., Losey, J.E., Jesse, L.H., Obrycki, J.J., Hufbauer, R., 2001. Effects of corn plants and corn pollen on monarch butterfly (Lepidoptera: Danaidae) oviposition behavior. Environmental Entomology 30, 495–500.

Tyson, T., Reardon, W., Browne, J.A., Burnell, A.M., 2007. Gene induction by desiccation stress in the entomopathogenic nematode *Steinernema carpocapsae* reveals parallels with drought tolerance mechanisms in plants. International Journal of Parasitology 37, 763-776.

Ugine, T.A., Wraight, S.P., Sanderson, J.P., 2007a. Effects of manipulating spray application parameters on efficacy of the entomopathogenic fungus *Beauveria bassiana* against western flower thrips, *Frankliniella occidentalis*, infesting greenhouse impatiens crops. Biocontrol Science and Technology 17, 193-219.

Ugine, T.A., Wraight, S.P., Sanderson, J.P., 2007b. A tritrophic effect of host plant on susceptibility of western flower thrips to the entomopathogenic fungus *Beauveria bassiana*. Journal of Invertebrate Pathology 96, 162-172.

Unruh, T.R., Lacey, L.A., 2001. Control of codling moth, *Cydia pomonella* (Lepidoptera: Tortricidae) with *Steinernema carpocapsae*: effects of supplemental wetting and pupation site on infection rate. Biological Control 20, 48-56.

Vachon, V., G. Préfontaine, F. Coux, C. Rang, L. Marceau, L. Masson, R. Brousseau, R. Frutos, J.L. Schwartz, R. Laprade. 2002. Role of helix three in pore formation by the *Bacillus thuringiensis* insecticidal toxin Cry1Aa. Biochemistry. 41, 6178-6184.

Vachon, V., Préfontaine, G., Rang, C., Coux, F., Juteau, M., Schwartz, J.L., Brousseau, R., Frutos, R., Laprade, R., Masson, L., 2004. Helix 4 mutants of the *Bacillus thuringiensis* insecticidal toxin Cry1Aa display altered pore-forming abilities. Applied and Environmental Microbiology 70, 6123-6130.

Vachon, V., Laprade, R., Scwartz J.L. 2012 Current models of the mode of action of *Bacillus thuringiensis* insecticidal crystal proteins: A critical review. Journal Invertebrate Pathology 111, 1-12.

Vail, P.V., Tebbets, J.S., Cowan, D.C., Jenner, K.E., 1991. Efficacy and persistence of a granulosis virus against infestations of *Plodia interpunctella* (Hüber) (Lepidoptera: Pyralidae) on raisins. Journal of Stored Products Research 27, 103-107.

Vail, P.V., Hoffmann, D.F., Tebbets, J.S., 1993. Autodissemination of *Plodia interpunctella* (Hüber) (Lepidoptera: Pyralidae) granulosis virus by healthy adults. Journal of Stored Products Research 29, 71-74.

Vail, P.V., Hostetter, D.L., Hoffmann, F., 1999. Development of multi-nucleocapsid polyhedroviruses (MNPVs) infectious to loopers as microbial control agents. Integrated Pest Management Reviews 4, 231-257.

Valicente, F., Macedo, C., Wolff, J., 2008. A new baculovirus isolate that doesn't cause liquefaction of the integument in *Spodoptera frugiperda* dead larvae. In: Proceedings XXIII International Congress of Entomology 6-12 July, 2008. Durban, South Africa, pp. 1232.

Van Beek, N., 2007. Can Africa learn from China? Fruit and Vegetable Technology 7, 32-33.

Van Beek, N., Davies, D. C., 2009. Baculovirus production in insect larvae. In: Murhammer, D.W. (Ed.), Methods in Molecular Biology 338, Baculovirus and Insect Cell Expression Protocols. Humana Press, Towata, USA, pp. 367-378.

van Frankenhuyzen, K., 2000. Application of *Bacillus thuringiensis* in forestry. In: Charles, J.-F., Delecluse, A., Nielsen-LeRoux, C. (Eds.), Entomopathogenic Bacteria: From Laboratory to Field Application. Kluwer Academic Publishers, Dordrecht, pp. 371-382.

van Frankenhuyzen, K., 2009. Insecticidal activity of *Bacillus thuringiensis* crystal proteins. Journal of Invertebrate Pathology 101, 1-16.

van Frankenhuyzen, K., Reardon, R.C., Dubois, N.R., 2007. Forest defoliators. In: Lacey, L.A., Kaya, H. K. (Eds.), Field Manual of Techniques in Invertebrate Pathology: Application and Evaluation of Pathogens for Control of Insects and Other Invertebrate Pests, 2nd Edition. Springer, Dordrecht, The Netherlands, pp. 481-504.

van Tol, R.W.H.M., van der Sommen, A.T.C., Boff, M.I.C., van Bezooijen, J., Sabelis, M.W., Smits, P.H., 2001. Plants protect their roots by alerting the enemies of grubs. Ecology Letters 4, 292-294.

Van Tol, R.W., Visser, J.H., Sabelis, M.W., 2002. Olfactory responses of the vine weevil, *Otiorhynchus sulcatus*, to tree odours. Physiological Entomology 27, 213-222.

Van Tol, R.W., Visser, J.H., Sabelis, M.W., 2004. Behavioural responses of the vine weevil, *Otiorhynchus sulcatus*, to semiochemicals from conspecifics, *O. salicicola*, and host plants. Entomologia Experimentalis et Applicata 110, 145-150.

van Tol, R.W.H.M., James, D.E., de Kogel, W.J., Teulon, D.A.J., 2007. Plant odours with potential for a push-pull strategy to control the onion thrips, *Thrips tabaci*. Entomologia Experimentalis et Applicata 122, 69–76.

Vega, F.E., Jackson, M.A., Mercadier, G., Poprawski, T.J., 2003. The impact of nutrition on spore yields for various fungal entomopathogens in liquid culture. World Journal of Microbiology and Biotechnology 19, 363-368.

Vega, F.E., Dowd, P.F., Lacey, L.A., Pell, J.K., Jackson, D.M., Klein, M.G., 2007. Dissemination of beneficial microbial agents by insects. In: Lacey, L.A., Kaya, H.K. (Eds.), Field Manual of Techniques in Invertebrate Pathology: Application and Evaluation of

Pathogens for Control of Insects and Other Invertebrate Pests, 2nd Edition. Springer, Dordrecht, pp. 127-146.

Vega, F.E., Posada, F., Aime, M.C., Pava-Ripoll, M., Infante, F., Rehner, S.A., 2008. Entomopathogenic fungal endophytes. Biological Control 46, 72-82.

Vega, F.E., Goettel, M.S., Blackwell, M., Chandler, D., Jackson, M. A., Keller, S., Koike, M., Maniania, N. K., Monzón, A., Ownley, B.H., Pell, J.K., Rangel, D.E.N., Roy, H.E., 2009. Fungal entomopathogens: new insights on their ecology. Fungal Ecology 2, 149-159.

Vega, F.E., Meyling, N.V., Luangsa-ard, J. J., Blackwell, M. 2012. Fungal entomopathogens. In: F.E. Vega, H.K. Kaya (Eds.). Insect Pathology, 2nd Edition. Academic Press, San Diego. In: pp. 172-220.

Venakumari, K., Rabindra, R. J., Srinivasa-Naik, C.D., Shubha, M. R., 2005. Field efficacy of nuclear polyhedrosis virus against red hairy caterpillar *Amsecta albistriga* on groundnuts in Karnatika (South India). Journal of Biological Control 19, 141-144.

Vey, A., Hoagland, R.E., Butt, T.M., 2001. Toxic metabolites of fungal biocontrol agents. In: Butt, T., Jackson, C., Magan, N. (Eds.), Fungi as Biocontrol Agents-Progress, Problems and Potential. CABI Press, Wallingford, UK, pp. 311-346.

Vidal, C., Fargues, J., 2007. Climatic constraints for fungal bioinsecticides. In: Ekesi, S., Maniania, N.K. (Eds.), Use of Entomopathogenic Fungi in Biological Pest Management. Research Signpost, Kerala, India, pp 39-55.

Vidal, C., Fargues, J., Rougier, M., Smits, N., 2003. Effect of air humidity on the infection potential of hyphomycete fungi as mycoinsecticides for *Trialeurodes vaporariorum*. Biocontrol Science and Technology 13, 183-198.

Vincent, C., Andermatt, M., Valero, J., 2007. Madex® and VirosoftCP4®, viral pesticides for codling moth control. In: Vincet, C., Goettel, M.S., Lazarovits, G. (Eds.), Biological Control: A Global Perspective. CAB International, Wallingford, pp. 336-343.

Vié, V., Van Mau, N., Pomarède, P., Dance, C.,Schwartz, J.L., Laprade, R., Frutos, R., Rang, C.,Masson, L., Heitz, F., Le Grimellec, C., 2001. Lipid-induced pore formation of the *Bacillus thuringiensis* Cry1Aa insecticidal toxin. Journal of Membrane Biology 180, 195-203.

Villani, M.G., Kreuger, S.R., Schroeder, P.C., Consolie, F., Consolie, N.H., Preston-Wilsey, L.M., Roberts, D.W., 1994. Soil application effects of *Metarhizium anisopliae* on Japanese beetle (Coleoptera: Scarabaeidae) behavior and survival in turfgrass microcosms. Environmental Entomology 23, 502-503.

Villani, M.G., Allee, L.L., Preston-Wilsey, L., Consolie, N., Xia, Y., Brandenburg, R.L., 2002. Use of radiography and tunnel castings for observing mole cricket (Orthoptera: Gryllotalpidae) behaviour in soil. American Entomologist 48, 42-50.

Waage J.K. 1997. Biopesticides at the crossroads IPM products or chemical clones. In "Microbial Insecticides: Novelty or Necessity?" British Crop Protection Council Proceeding Monograph Series No 68. pp. 11-19.

Wang, C., St. Leger, R.J., 2007. A scorpion neurotoxin increases the potency of a fungal insecticide. Nature Biotech 25, 1455-1456.

Wang, C., Fan, M., Li, Z., Butt, T.M., 2004. Molecular monitoring and evaluation of the application of the insect-pathogenic fungus *Beauveria bassiana* in southeast China. Journal of Applied Microbiology 96, 861-870.

Wang, C., Hu, G., St. Leger, R.J., 2005. Differential gene expression by *Metarhizium anisopliae* growing in root exudate and host (*Manduca sexta*) cuticle or haemolymph reveals mechanisms of physiological adaptation. Fungal Genetics and Biology 42, 704-718.

Wang, Y., Bilgrami, A.L., Shapiro-Ilan, D., Gaugler, R., 2007. Stability of entomopathogenic bacteria, *Xenorhabdus nematophila* and *Photorhabdus luminescens*, during in vitro culture. Journal of Industrial Microbiology and Biotechnology 34, 73–81.

Wei, J.-Z., Hale, K., Carta, L., Platzer, E., Wong, C.,Fang, S.-C., Aroian, R. V., 2003. *Bacillus thuringiensis* crystal proteins that target nematodes. Proceedings of the National Academy of Science 100, 2760-2765.

Wekesa V. W., Maniania N. K., Knapp M., Boga H. I., 2005. Pathogenicity of *Beauveria bassiana* and *Metarhizium anisopliae* to the tobacco spider mite *Tetranychus evansi*. Experimental and Applied Acarology 36, 41-50.

Whalon, M.E., Wingerd B.A., 2003. Bt: mode of action and use. Archives of Insect Biochemistry and Physiology 54, 200-211.

Williams, C.D., Dillon, A.B., Harvey, C.D., Hennessy, R., Namara, L.M., Griffin, C.T., 2013b. Control of a major pest of forestry, *Hylobius abietis*, with entomopathogenic nematodes and fungi using eradicant and prophylactic strategies. Forest Ecology and Management 305, 212-222.

Williams, R.N., Fickle, D.S., Grewal, P.S., Dutcher, J., 2010. Field efficacy against the grape root borer *Vitacea polistiformis* (Lepidoptera: Sesiidae) and persistence of *Heterorhabditis* *zealandica* and *H. bacteriophora* (Nematoda: Heterorhabditidae) in vineyards. Biological Control 53, 86-91.

Williams, T., Goulson, D., Caballero, P., Cisneros, J., Martínez, A. M., Chapman, J. W., Roman, D. X., Cave, R.D., 1999. Evaluation of a baculovirus bioinsecticide for small-scale maize growers in Latin America. Biological Control 14, 67-75.

Williams, T., Aredondo-Bernal, H.C., Roderigez-del-Bosque, L.A., 2013a. Biological pest control in Mexico. Annual Review of Entomology 58, 119-40.

Wolfenbarger, L.L., Naranjo, S.E., Lundgren, J.G.., Bitzer, R.J., Watrud, L.S., 2008. Bt crop effects on functional guilds of non-target arthropods: a meta-analysis. PLoS One 3, e2118.

Wraight, S.P., Ramos, M.E., 2002. Application parameters affecting field efficacy of *Beauveria bassiana* foliar treatments against Colorado potato beetle *Leptinotarsa decemlineata.* Biological Control 23, 164–178.

Wraight, S.P., Hajek, A.N. 2009. Manipulation of arthropod pathogens for IPM. In: Radcliff, E.B., Hutchison, W.D., Cancelado, R.E. (Eds), Integrated Pest Management: concepts, tactics, strategies and case studies. Cambridge University Press, Cambridge, UK, pp. 131-150.

Wraight, S. P., Carruthers, R. I., Jaronski, S. T., Bradley, C. A., Garza, C. J., Galaini-Wraight, S., 2000. Evaluation of the entomopathogenic fungi *Beauveria bassiani* and *Paecilomyces fumosoroseus* for microbial control of the silverleaf whitefly, *Bemisia argentifolii*. Biological Control 17, 203-217.

Wraight, S.P., Jackson, M.A., de Kock, S.L., 2001. Production, stabilization and formulation of fungal biocontrol agents. In: Butt, T., Jackson, C., Magan, N. (Eds.), Fungi as Biocontrol Agents-Progress, Problems and Potential. CABI Press, Wallingford, UK, pp. 253-287.

Wraight, S. P., Inglis, G. D., Goettel, M. S., 2007a. Fungi. In: Lacey, L.A., Kaya, H. K. (Eds.), Field Manual of Techniques in Invertebrate Pathology: Application and Evaluation of Pathogens for Control of Insects and Other Invertebrate Pests, 2nd Edition. Springer, Dordrecht, The Netherlands, pp. 223-

Wraight, S.P., Sporleder, M., Poprawski, T.J., Lacey, L.A., 2007b. Application and evaluation of entomopathogens in potato. In: Lacey, L.A., Kaya, H.K. (Eds.), Field Manual of Techniques in Invertebrate Pathology: Application and Evaluation of Pathogens for Control of Insects and Other Invertebrate Pests, 2nd Edition. Springer, Dordrecht, The Netherlands, pp. 329-359.

Wraight, S.P., Lacey, L.A., Kabaluk, J.T., Goettel, M.S., 2009. Potential for microbial biological control of coleopteran and hemipteran pests of potato. Fruit, Vegetable and Cereal Science and Biotechnology 3, 25-38.

Wright, D.J., Peters, A., Schroer, S., Fife, J.P., 2005a. Application technology. In: Grewal, P.S., Ehlers, R.-U., Shapiro-Ilan, D.I., (Eds.), Nematodes as Biocontrol Agents. CABI, Wallingford, UK, pp. 91-106.

Wu, J., Ridgway, H., Carpenter, M., Glare, T., 2008. Efficient transformation of *Beauveria bassiana* by *Agrobacterium tunefaciens*-mediated insertional mutagenesis. Australasian Plant Pathology 37, 537-542.

Wu, K., Mu, W., Liang, G., Guo, Y., 2005. Regional reversion of insecticide resistance in *Helicoverpa armigera* (Lepidoptera: Noctuidae) is associated with the use of Bt cotton in northern China. Pest Management Science 61, 491-498.

Yang Z., 2007. Recent Advances in the Biological Control of Invasive Forest Pests in China. International Workshop on Biological Control of Invasive Species of Forests Beijing, P.R. China September 20-25, 2007.pp 9-20.

(http://www.fs.fed.us/foresthealth/technology/pdfs/IWBCISF_proceedings.pdf. Accessed 3 February 2014)

Yang M.M., Meng, L.L., Zang, Y,A., Wang, Y,Z., Qu,L.J., Wang, Q.H., Ding, J.Y., 2012. Baculoviruses and insect pest Control in China. African Journal of Microbiology Research, 6, 214-218.

Zamora-Avilés, N. Alonso-Vargas, J., Pineda, S., Isaac-Figueroa, J., Lobit, P., Martínez-Castillo, A. M., 2013. Effects of a nucleopolyhedrovirus in mixtures with azadirachtin on *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae) larvae and viral occlusion body production, Biocontrol Science and Technology 23, 521-534,

Zangerl, A.R., McKenna, D., Wraight, C.L., Carroll, M., Ficarello, P., Warner, R., Berenbaum, M.R., 2001. Effects of exposure to event 176 *Bacillus thuringiensis* corn pollen on monarch and black swallowtail caterpillars under field conditions. Proceedings of the National Academy of Sciences USA 98, 11908–11912.

Zeddam, J.L., Arroyo-Cruzado, J., Luna-Roderiguez, J., Ravallec, M., 2003b. A new nucleopolyhedrovirus from the oil-palm leaf-eater *Euprosterna elaeasa* (Lepidoptera: Limacodidae): preliminary characterization and field assessment in Peruvian plantation. Agriculture Ecosystems and Environment 96, 69-75.

Zenner, A.N.R.L., O'Callaghan, K. M., Griffin, C.T., 2014. Lethal fighting in nematodes is dependent on developmental pathway: Male-male fighting in the entomopathogenic nematode *Steinernema longicaudum*. PLoS ONE 9(2), e89385.

Zethner, O., 1980. Control of *Agrotis segetum* (Lep: Noctuidae) in root crops by granulosis virus. BioControl 25, 27-35.

Zethner, O., Khan, B.M., Chaudhry, M.I., Bolet, B., Khan, S., Khan, H., Gul, H., Øgaard, L., Zaman, M., Nawaz, G., 1987. *Agrotis segetum* granulosis virus as a control agent against field populations of *Agrotis ipsilon* and *A. Segetum* [*Lep.: Noctuidae*] on tobacco, okra, potato and sugar beet in northern Pakistan. BioControl 32, 449-455.

Zhang, X., Candas, M., Griko, N.B., Taussig, R., Bulla, L.A. Jr., 2006. A mechanism of cell death involving an adenylyl cyclase/PKA signaling pathway is induced by the Cry1Ab toxin of *Bacillus thuringiensis*. Proceedings of the National Academy of Sciences USA 103, 9897-9902.

Zhou, X., Kaya, H.K., Heungens, K., Goodrich-Blair, H., 2002. Response of ants to a deterrent factor(s) produced by the symbiotic bacteria of entomopathogenic nematodes. Applied and Environmental Microbiology 68, 6202-6209.

Zhu, H., Grewal, P.S., Reding, M.E., 2011. Development of a desiccated cadaver delivery system to apply entomopathogenic nematodes for control of soil pests. Applied Engineering in Agriculture 27, 317-324.

Zichová, T., Stará, J., Kundu, J. K., Eberle K.E., and Jehle, J.E., 2013. Resistance to *Cydia pomonella* granulovirus follows a geographically widely distributed inheritance type within Europe. BioControl 58, 525-534.

Zimmermann, G., 1992. Use of the fungus, *Beauveria brongniartii*, for the control of European cockchafers, *Melolontha* spp. in Europe. In: Jackson, T.A., Glare, T.R. (Eds.), Use of Pathogens in Scarab Pest Management. Intercept Limited, Hampshire, UK, pp. 199-208.

Zimmermann, G., 2007a. Review on safety of the entomopathogenic fungi *Beauveria bassiana* and *Beauveria brongniartii*. Biocontrol Science and Technology 17, 553-596.

Zimmermann, G., 2007b. Review on safety of the entomopathogenic fungus *Metarhizium anisopliae*. Biocontrol Science and Technology 17, 879-920.

Zimmermann, G., 2008. The entomopathogenic fungi *Isaria farinosa* (formerly *Paecilomyces farinosus*) and the *Isaria fumosorosea* species complex (formerly known as *Paecilomyces fumosoroseus*): biology, ecology and its use in biological control. Biocontrol Science and Technology 18, 865-901.

Table 1. Entomopathogenic viruses that have been used for biological control of insect pests.

Common and Species Names	Targeted insects	Producer	Selected References
Baculovirus	Principally Lepidoptera, some Hymenoptera and Diptera		Miller (1997), Moscardi (1999, 2007), Theilmann et al. (2005), Szewczyk et al. (2009), Harrisson and Hoover (2012)
Corn earworm NPV (HezeSNPV)	*Helicoverpa zea*: Corn earworm, Tomato fruitworm, Tobacco budworm. *Heliothis virescens*	Certis (USA)	Ignoffo (1999), Rowley et al. (2011)
Cotton bollworm NPV (HearNPV)	*Helicoverpa armigera,* Cotton bollworm, Podborer,	Andermatt, (Switzerland) AgBioTech (Australia) Jiyuan Baiyun Industry Company Ltd (China), BioControl Research Labs (India), Kenya Biologics (Kenya), plus other producers in India, China,	Grzywacz (2010), Hauxwell et al. (2010), Rabindra and Rowley et al. (2011), Yang et al., (2012), Gwynn (2014).
Diamond back moth GV (PlxyGV)	*Plutella xylostella*	Jiyuan Baiyun Industry Company Ltd (China)	Grzywacz et al. (2004), Farrar et al. (2007), Yang et al. (2012)
Unbarred Spodoptera moth (army worm NPV (SdalNPV)	*Spodoptera albula* (*sunia*)	Agricola el Sol (Guatamala)	Moscardi (1999)
Beet armyworm NPV (SpexMNPV)	*Spodoptera exigua*	Andermatt, (Switzerland) Certis (USA) Jiyuan Baiyun Industry Company Ltd, (China) BioTech (Thailand)	Kolodny-Hirsch et al. (1997), Lasa et al. (2007), Sun and Peng (2007), Gwynn (2014)
Egyptian Cotton Leafworm NPV	*Spodoptera littoralis*	Andermatt (Switzerland)	Jones et al. (1994)

(SpliNPV)			
Tobacco armyworm NPV (SpltNPV)	*Spodoptera litura*	Biocontrol Research Lab, Ajay Biotech, Bassarass Biocontrol, Biotech International, BioControl Research Labs (India) Jiyuan Baiyun Industry Company Ltd, (China)	Nakai and Cuc (2005), Department of Biotechnology India (2007), Kunimi (2007), Yang et al. (2012)
Gypsy moth, NPV (LydiMNPV)	*Lymantria dispar*	USDA , (USA) Sylvar Technology (Canada) Andermatt (Switzerland)	Podgewaite (1999)
Velvetbean caterpillar, NPV (AngeMNPV)	*Anticarsia gemmatalis*	Coodetec. CNP So, Nova Era Biotechnologica Agricola, Nitral Urbana Laboratorios, Coop Central Milenio Agro Ciencias (Brazil)	Moscardi (2007), Sosa-Gómez et al. (2008), Moscardi et al. (2011), Panazzi (2013)
Red headed pine sawfly NPV (NeleNPV)[1]	*Neodiprion lecontei*	Sylvar Technology (Canada)	Cunningham (1995)
Douglas fir tussock moth NPV (OrpsNPV)	*Orygia pseudotsugata*	Canadian Forest Service	Martignoni (1999)
Balsam fir sawfly NPV (NeabNPV)	*Neodiprion abietis*	Sylvar Technology (Canada)	Lucarotti et al. (2007), Moreau and Lucarotti (2007)
Codling moth GV (CpGV)	*Cydia pomonella*	Certis (USA), BioTepp (Canada), Arysta Lifscience(France), Andermatt (Switzerland), Hoerst (Germany), BioBest (Belgium), Arysta Life Science (France), Agro Roca (Argentine)	Tanada (1964), Cross et al. (1999), Arthurs et al. (2005); Eberle and Jehle (2006), Lacey et al. (2008b)
False Codling Moth GV	*Cryptophlebia*	Andermatt	Singh et al. (2003),

(CrleGV)	*leucotreta*	(Switzerland), River Bioscience (South Africa)	Moore et al. (2004b)
Potato tubermoth GV (PhopGV)	*Phthorimaea operculella*	Centro Internacional de la Papa (Peru), Proinpa (Bolivia)	Sporleder (2003), Arthurs et al. (2008b), Kroschel and Lacey (2008), Lacey and Kroschel (2009)
Summer fruit totrix GV (AdorGV)	*Adoxophyes orana*	Andermatt (Switzerland)	Blommers (1994), Cross et al. (2005), Nakai (2009)
Tea tortrix (HomaGV)	*Homona magnanima*	Arysta life science (Japan)	Kunimi (2007), Nakai (2009)
Smaller Tea tortrix GV (AdhoGV)	*Adoxophyes honmai*	Arysta life science (Japan)	Nakai et al. (2002), Nakai (2009)
Alfalfa looper NPV (AucaMNPV)	Noctuidae	Agricola el Sol (Guatamala)	Vail et al. (1999), Yang et al. (2012)
Cabbage looper (TrniSNPV)[1]	*Trichoplusia ni*	Andermatt (Switzerland)	Vail et al. (1999)
Tea geomotrid EcobNPV	*Extropic obliqua*	Small scale commercial production China *	Sun and Peng (2007), Yang et al. (2012)
Tea tussock moth (Eups NPV)	*Euproctis pseudoconspersa*	Small scale commercial production China *	Sun and Peng (2007), Yang et al. (2012)
Tea Moth (BuzuNPV)	*Buzura suppressaria*	Small scale commercial production China *	Sun and Peng (2007), Yang et al. (2012)
Teak Defoliator (HypeNPV)	*Hyblea peura*	Kerala Forest Research Institute (India)	Nair et al. (1996)
Imported cabbageworm (PiraGV)	*Artogeia (Pieris) rapae*	Registered in China Small scale commercial production China *	Yang et al. (2012)
Oriental armyworm, (LeseNPV)	*Leucania (Mythimna) separata*	Registered in China Small scale commercial	Yang et al. (2012)

		production China *	
Reoviridae			
Masson pine moth cypovirus (CPV)	*Dendrolimus punctatus*	Registered in China Small scale commercial production China *	Peng et al. (2000), Yang (2007) Yang et al. (2012)
Parvoviridae			
Cockroach densonucleosis virus (DNV)	*Periplaneta fuliginosa*	Registered in China Small scale commercial production China *	Bergoin and Thijsen (1997), Yang et al. (2012)
Nudiviruses			
Oryctes virus	*Oryctes rhinoceros*	Not commercially produced but locally produced for autodissemination	Jackeson et al. (2005), Huger (2005), Ramle et al. (2005), Jackson (2009)

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Table 2. Entomopathogenic bacteria used for control of insect pests of major crops, forest, turf, humans and domesticated animals.

Bacterial Species	**Major Targeted Habitat**	**Examples of Major Pest Orders**	**Selected References**
Bacillus thuringiensis sub-species *kurstaki*[1]	Row crops, forests, orchards	Lepidoptera: numerous families and species	Glare and O'Callaghan (2000), Federici (2005), Huang et al. (2007), Lacey et al. (2007), van Frankenhuyzen (2009), Jurat-Fuentes and Jackson (2012),
B. thuringiensis sub-species *aizawai*[1]	Row crops, orchards	Lepidoptera	Tabashnik et al. (1993), Glare and O'Callaghan (2000), Mashtoly et al. (2011)
B. thuringiensis sub-species *tenebrionis*[1]	Potato	Coleoptera: Chrysomelidae, predominantly *Leptinotarsa decemlineata*	Kreig et al. (1983), Langenbrusch (1985), Gelernter (2002)
B. thuringiensis sub-species *israelensis*[1]	Diverse lentic and lotic aquatic habitats	Diptera: Culicidae and Simuliidae	Lacey and Merritt (2003), Lacey (2007), Skovmand et al. (2007), Despres et al. (2011)
B. thuringiensis sub-species *japonensis* strain Buibui	Lawn and turf	Coleoptera: Scarabaeidae	Alm et al. (1997), Klein et al. (2007), Mashtoly et al. (2010)
Lysinibacillus sphaericus[1]	Lentic aquatic habitats	Diptera: Culicidae	Charles et al. (2000), Lacey (2007), Skovmand et al. (2007)
Paenibacillus popilliae	Lawn and turf	Coleoptera: Scarabaeidae: *Popillia japonica*	Klein et al. (2007), Koppenhöfer et al. (2012)
Serratia entomophila[1]	Pasture	Coleoptera: Scarabaeidae: *Costelytra zealandica*	Jackson et al. (1992, 2001), Jackson (2003), Jackson and Klein (2006)

[1]commercially produced

4472 Table 3. An overview of the entomopathogenic fungi that have been developed for microbial
4473 control of insect pests.[1]
4474

Species Names	Targeted insects	Produced in	Selected References
Aschersonia aleyrodis	Hemiptera (Aleyrodidae)	Russia	Fransen, 1990; Meekers et al., 2002; Lacey et al., 2008; McCoy et al., 2009
Beauveria bassiana sensu lato	Acari, Coleoptera, Diplopoda, Diptera, Hemiptera, Hymenoptera, Isoptera, Lepidoptera, Orthoptera, Siphonoptera, Thysanoptera,	Africa, Asia, Australia, Europe, South & North America	de la Rosa et al., 2000; Wraight et al., 2000, 2007b; Chandler et al., 2005; Wekesa et al., 2005; Brownbridge et al., 2006; Labbé et al., 2009
Beauveria brongniartii	Coleoptera (Scarabaeidae)	Europe, Colombia, Reunion Island	Zimmermann, 1992; Keller, 200; Keller et al., 2003; Dolci et al., 2006; Townsend et al., 2010
Conidiobolus thromboides	Acari Hemiptera, Thysanoptera	Colombia, India, South Africa	Papierok and Hajek, 1997; Nielsen and Hajek, 2005; Hajek et al., 2012
Hirsutella thompsonii	Acari	India	McCoy, 1981; Chandler et al., 2000, 2005; McCoy et al., 2009
Isaria fumosorosea	Acari, Diptera, Coleoptera, Hemiptera, Thysanoptera,	Belgium, Colombia, Mexico, USA, Venezuela	Wraight et al., 2000, 2007; Lacey et al., 2008, 2011; Zimmermann, 2008
Lagenidium giganteum	Diptera (Culicidae)	USA	Kerwin and Petersen, 1997; Skovmand et al., 2007
Lecanicillium longisporum	Hemiptera	Brazil, Netherlands	Bird et al., 2004; Down et al., 2009; Kim et al., 2009
Lecanicillium muscarium	Acari, Hemiptera, Thysanoptera	Netherlands, Russia	Chandler et al., 2005; Cuthbertson and Walters, 2005; Burges, 2007; Goettel et al., 2008
Metarhizium anisopliae sensu lato	Acari, Blattoidea, Coleoptera, Diptera, Hemiptera, Isoptera, Lepidoptera, Orthoptera,	Africa, Asia, Australia, Europe, South, Central & North America	de la Rosa et al., 2000; Chandler et al., 2005; Wekesa et al., 2005; Jaronski and Jackson, 2012; Lacey et al., 2011

Metarhizium acridum	Orthoptera	Australia, South Africa, USA	Lomer et al, 1999. 2001; Thomas, 2000
Nomuraea rileyi	Lepidoptera	Columbia, India	Moscardi and Sosa-Gomez, 2007; Thakre et al., 2011

[1] Condensed and modified from de Faria and Wraight, 2007. For up to date information on products registered in the OECD Countries, visit https://www5.agr.gc.ca/MPDD-CPM/search-recherche.do?lang=eng
For information on the production and successful use of entomopathogenic fungi as microbial pesticides in Latin America see Alves et al., 2008.

Table 4. Efficacy and commercialization of entomopathogenic nematodes for suppression of some major insect pests.

Pest Common name	**Pest** **Scientific name**	**Key Crop(s) targeted**	**≥ 75% Efficacy Observed**[a]	**Targeted Commercially**[c]
Artichoke plume moth	*Platyptilia carduidactyla*	Artichoke	Yes (Sc)	Yes
Armyworms	Lepidoptera: Noctuidae[b]	Vegetables	Yes (Sc, Sf, Sr)	Yes
Banana moth	*Opogona sachari*	Ornamentals	Yes (Hb, Sc)	Yes
Banana root borer	*Cosmopolites sordidus*	Banana	Yes (Sc, Sf, Sg)	Yes
Billbug	*Sphenophorus* spp. (Coleoptera: Curculionidae)	Turf	Yes (Hb,Sc)	Yes
Black cutworm	*Agrotis ipsilon*	Turf, vegetables	Yes (Sc)	Yes
Black vine weevil	*Otiorhynchus sulcatus*	Berries, ornamentals	Yes (Hb, Hd, Hm, Hmeg, Sc, Sg)	Yes
Borers	*Synanthedon* spp. and other sesiids	Fruit trees & ornamentals	Yes (Hb, Sc, Sf)	Yes
Cat flea	*Ctenocephalides felis*	Home yard, turf	No	Yes
Chinch bugs	**Hemiptera: Blissidae**	Turf	No	Yes
Citrus root weevil	*Pachnaeus* spp. (Coleoptera: Curculionidae	Citrus, ornamentals	Yes (Sr, Hb)	Yes
Codling moth	*Cydia pomonella*	Pome fruit	Yes (Sc, Sf)	Yes
Corn earworm	*Helicoverpa zea*	Vegetables	Yes (Sc, Sf, Sr)	Yes
Corn rootworm	*Diabrotica* spp.	Vegetables	Yes (Hb, Sc)	Yes
Cranberry girdler	**Chrysoteuchia topiaria**	Cranberries	Yes (Sc)	Yes
Crane fly	**Diptera: Tipulidae**	Turf	Yes (Sc)	Yes
Diamondback moth	***Plutella xylostella***	Vegetables	No	Yes
Diaprepes root weevil	***Diaprepes abbreviatus***	Citrus, ornamentals	Yes (Hb, Sr)	Yes
Fungus gnats	Diptera: Sciaridae	Mushrooms, greenhouse	Yes (Sf, Hb)	Yes
German cockroach	*Blattella germanica*	Household	No	Yes
Grape root borer	*Vitacea polistiformis*	Grapes	Yes (Hz)	No
Iris borer	*Macronoctua onusta*	Iris	Yes (Hb, Sc)	Yes
Large pine weevil	*Hylobius albietis*	Forest plantings	Yes (Hd, Sc)	Yes

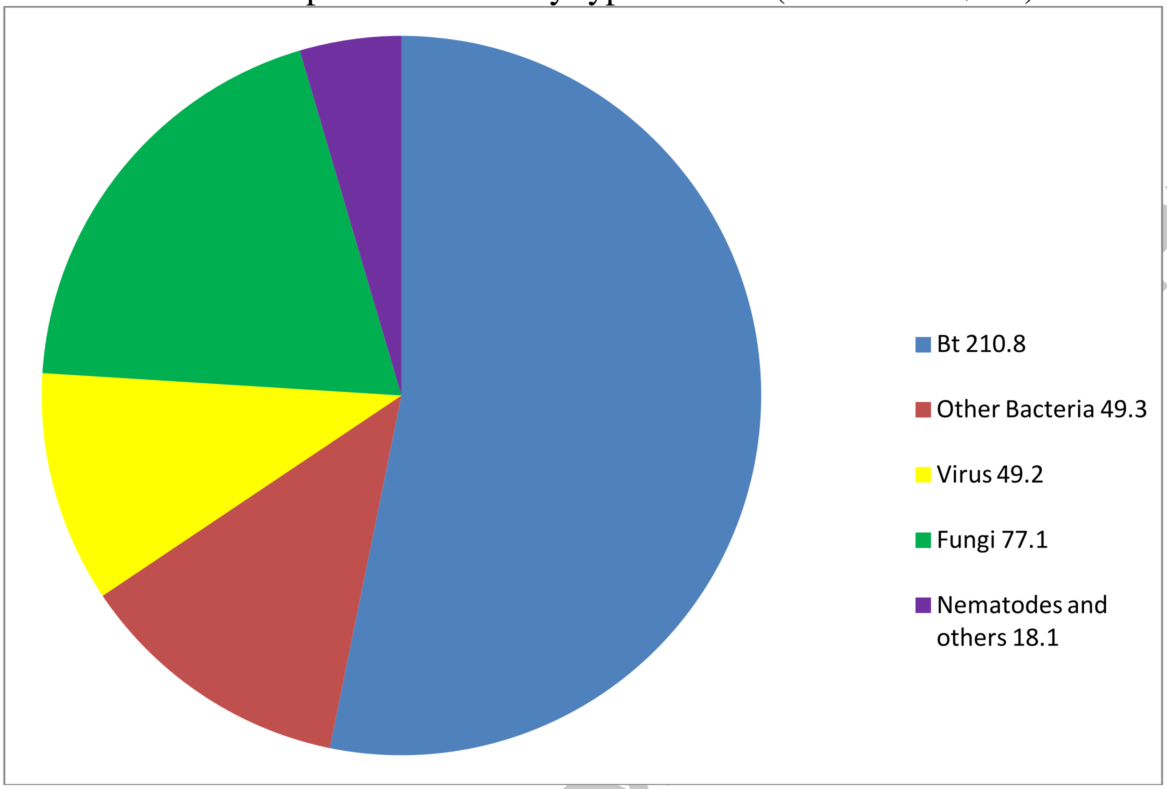
Leafminers	*Liriomyza* spp. (Diptera: Agromyzidae)	Vegetables, ornamentals	Yes (Sc, Sf)	Yes
Mint flea beetle	*Longitartsus waterhousei*	Mint	No	Yes
Mint root borer	*Fumibotys fumalis*	Mint	No	Yes
Mole crickets	*Scapteriscus* spp.	Turf	Yes (Sc, Sr, Scap)	Yes
Navel orangeworm	*Amyelois transitella*	Nut and fruit trees	Yes (Sc)	Yes
Oriental fruit moth	*Grapholita molesta*	Fruit trees	Yes (Sf)	No
Pecan weevil	*Curculio caryae*	Pecan	Yes (Sc)	Yes
Plum curculio	*Conotrachelus nenuphar*	Fruit trees	Yes (Sr)	Yes
Scarab grubs	Coleoptera: Scarabaeidae	Turf, ornamentals	Yes (Hb, Sc, Sg, Ss, Hz)[b]	Yes
Shore flies	***Scatella* spp.**	Ornamentals	Yes (Sc, Sf)	Yes
Sod webworms	Lepidoptera: Pyralidae	Turf	No	Yes
Strawberry root weevil	*Otiorhynchus ovatus*	Berries	Yes (Hm)	Yes
Sugarbeet weevil	*Temnorhinus mendicus*	Sugar beets	Yes (Hb, Sc)	No
Sweetpotato weevil	*Cylas formicarius*	Sweet potato	Yes (Hb, Sc, Sf)	Yes
Wireworms	Coleoptera: Elateridae	Vegetables	No	Yes

[a] At least one scientific paper reported ≥ 75% suppression of these pests in the field or greenhouse. Hb=*Heterorhabditis bacteriophora*, Hd = *H. downesi,* Hm= *H. marelatus*, Hmeg = *H. megidis*, Hz = *H. zealandica,* Sc=*Steinernema carpocapsae*, Sf=*S. feltiae*, Sg=*S. glaseri*, Sk = *S. kushidai,* Sr=*S. riobrave*, Sscap=*S. scapterisci, Ss = S. scarabaei*.

[b] Efficacy against various pest species within this group varies among nematode species.

[c] http://www.biocontrol.entomology.cornell.edu/pathogens/nematodes.php

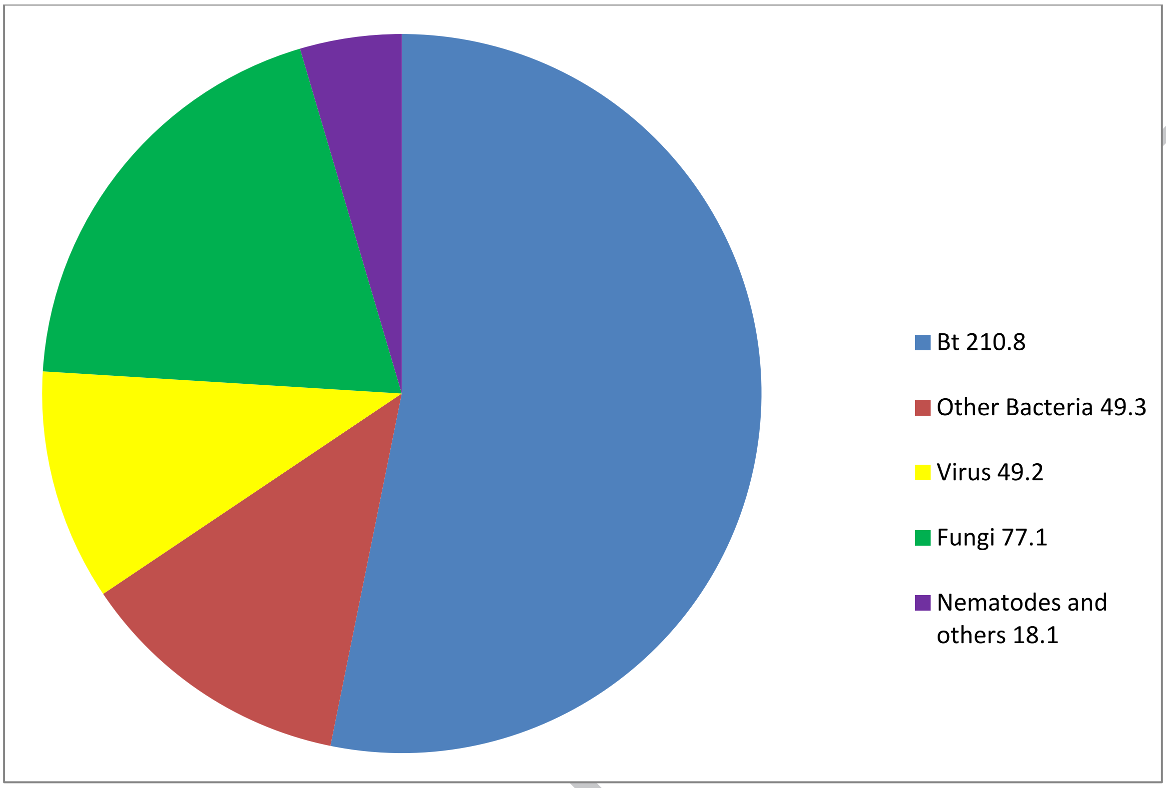
Estimated world biopesticide sales by type in 2010 (millions of $US).



CPL Business Consultants (2010) The 2010 Worldwide Biopesticides Market Summary, (Vol. 1), CAB International Centre. Wallingford.

*Figure

Figure 1. Estimated world biopesticide sales by type in 2010 (millions of $US).



CPL Business Consultants (2010) The 2010 Worldwide Biopesticides Market Summary, (Vol. 1), CAB International Centre. Wallingford.

*Figure

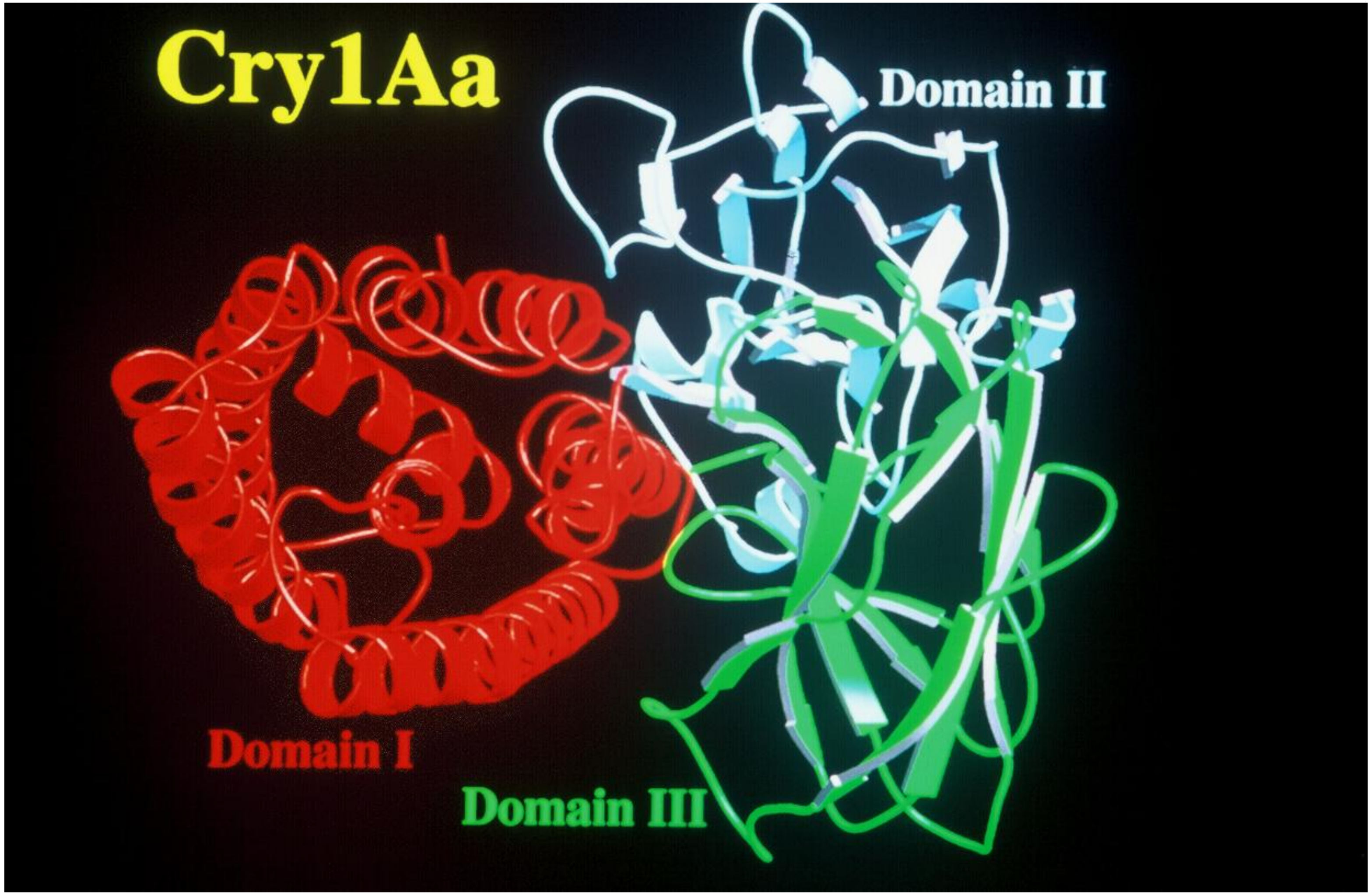


Figure 2. Apical ribbon view representing the 3-D structure of the *Bacillus thuringiensis* Cry1Aa toxin.
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