Pest Technology ©2008 Global Science Books

Sustainable Biocontrol of Apple Insect Pests

Mark W. Brown*

Appalachian Fruit Research Station, U.S. Department of Agriculture, Agricultural Research Service, Kearneysville, WV, USA

Correspondence: * Mark.Brown@ARS.USDA.GOV

ABSTRACT

Biocontrol of insect pests is a cornerstone to sustainable production of apples and other crops. The ecology of orchards lends itself to the application of many management options which will enhance the sustainability of biocontrol. Orchards remain in place for decades, allowing for an evolution of a stable, mature community of biological control species. Management tactics such as companion plants, interplanting, windbreaks and mulches have all been shown to lead to an increase in the abundance of insect natural enemies and higher rates of biocontrol. These tactics also have limitations in their implementation in commercial orchards. More research is needed to re-design the structure of apple orchards to incorporate sustainable biocontrol methods and optimize production. Biocontrol is an ecosystem service and as such needs to be studied holistically rather than with the more traditional reductionist science typically used in agricultural research.

Keywords: companion plants, compost, conservation biological control, ecosystem service, extrafloral nectar, interplanting, mulch

CONTENTS

INTRODUCTION

Temperate tree fruit orchards provide an ideal opportunity to establish a sustainable environment for biocontrol. Orchards have temporal stability remaining undisturbed for 20 years or more and provide a multitude of habitats within an architecturally complex three-dimensional space (Brown 1999). The combination of temporal stability and diversity in microhabitats produces opportunities to create a functionally diverse biodiversity which results in biocontrol of numerous pests (Brown 2001a). In addition to the characteristics of fruit trees in the orchard the entire agroecosystem must be considered: including the rhizoshpere, detritus food web on the soil surface, plants other than fruit trees in the orchard and the food web they support, and the surrounding habitats that provide both pest and beneficial colonists to the orchard. All of these components of the agroecosystem can contribute to the sustainability of biocontrol in the orchard, or if improperly managed, to its non-sustainability.

Originating in central Asia, apple (*Malus* x *domestica*) has been cultivated in temperate zones around the world. Wherever apple has been planted it has developed a large and diverse arthropod community (e.g.; Slingerland and Crosby 1914; Southwood 1961; Mészáros 1984) comprised of native and exotic pest and beneficial species. The importance of apple production, the semi-permanence of orchards, and the complex nature of the apple ecosystem has led to a long history of research on the arthropod community on apple and its management (Hoyt and Burts 1974). It has long been known that reducing the use of synthetic insecticides will increase the level of biocontrol for many insect pests (Pickett and Patterson 1953). Early research in eastern Canada on the judicious use of chemical insecticides with biocontrol (Pickett *et al*. 1956) was some of the earliest work that let to the development of the concepts of integrated pest management. Integrated fruit production of apples in Europe was one of the earlier attempts at providing guidelines for sustainable agriculture based on ecologically sound management (Sansavini 1997). Apple production, as well as all other agricultural production systems, is now at the stage where further advances are needed to address issues of sustainability. It is no longer feasible to rely on treating the symptoms of unbalanced ecosystems through therapeutic actions but rather to address the underlying imbalances of the system for a more sustainable approach to production (Lewis *et al*. 1997). The next advancement in apple pest management needs to include the redesign of what we consider to be the orchard ecosystem so that the goals of productivity are optimized with sustainability of the ecosystem; economically, environmentally and socially (Hill *et al.* 1999). Reliance on a sustainable biocontrol of insect pests will be a cornerstone to the realization of sustainable apple production.

Received: 20 February, 2008. Accepted: 14 April, 2008.

Invited Mini-Review

In this review, the research being done to provide tactics for sustainable biocontrol of apple insect pests is reviewed. Individually, and combined, these tactics should prove to be useful in the development of a redesigned apple ecosystem that is sustainable.

ECOLOGICAL CHARACTERISTICS

The apple ecosystem can be thought of as an archipelago within a sea of other habitats with varying densities of suitable host plants for insect pests and natural enemies, thus mimicking interactions described in island biogeography theory (MacArthur and Wilson 1963; Whalon and Croft 1986). Apple orchards can be of various sizes and at different distances from other orchards. In some regions, such as in eastern North America and Europe, there are numerous wild apple and other host plants in the habitats between orchards (Brown and Adler 1989; Szentkirályi and Kozár 1991), whereas in other regions, such as the arid western US, intervening habitats have very few alternate hosts (Rathman and Brunner 1988). Even in regions where apple orchard islands are surrounded by few alternate hosts there is significant immigration into the orchard from the regional species pool (Miliczky and Horton 2005). It was concluded that at least in regions rich in alternate hosts, the insect community in apple is determined largely by the regional extra-orchard vegetation diversity (Szentkirályi and Kozár 1991).

The insect community in the apple orchard ecosystem in eastern North America is similar to Europe in that there are numerous alternate hosts for pests and natural enemies in habitats interspersed between orchards. However, eastern North American insect community structure in apple seems to be determined by the intensity of external disturbances. Diversity, as measured by several diversity indices, and species composition of the phytophagous insect community throughout the mid-Atlantic region of eastern North America was more similar among orchards with similar management intensity than within regions (Brown and Adler 1989). This phytophagous insect community was nearly identical in insecticide-sprayed orchards from New York to Virginia, a distance spanning 750 km; but within a region, among orchards within 15 km, the fauna in an insecticide-treated orchard was much different from that in an unmanaged orchard. A similar trend was found among the micro-Lepidoptera in Michigan, USA (Strickler and Whalon 1985).

The development of the phytophagous insect community in West Virginia, USA, demonstrates the importance of the temporal stability of the apple ecosystem (Brown and Welker 1992). Three newly planted apple orchards were monitored for the first five years after planting. One of the orchards was managed with standard horticultural practices and insecticides, one managed with standard horticultural practices but no insecticides, and one was left unmanaged. For the first three years there were no differences in the phytophagous communities of insects among the three orchards. Only in the fourth year did the insect community in the insecticide treated orchard begin to show differences from the two orchards without insecticide use. All these orchards were within 10 km and were being colonized from the same general species pool. Immigration into these orchards began with species from the early succession stage; only after the communities not treated with insecticides began to evolve into a more mature structure did climax type species begin to colonize. These climax species were not able to establish in the insecticide treated orchards because the use of insecticides kept the community from maturing, keeping it in a perpetual state of early succession (Southwood 1977; Brown 1999).

Another characteristic of an insect community surrounded by a large species pool of potential colonizers is that it can be very resilient to perturbations. Two apple orchards, only 50 m apart and thus exposed to the same species pool of colonizers, previously untreated with insecticides were used to test the insect communities' resilience to a major perturbation (Brown 1993). One orchard was treated with three applications of a synthetic pyrethroid insecticide, a very broad-spectrum insect toxin, within ten weeks and the other was left untreated as a control. There was an initial drastic reduction in numbers of individuals and species in the treated orchard. By the end of the summer following insecticide applications there were no differences between the two communities. The ability of the insect community, especially the insectivores, to recover from a severe disruption will be critical in the development of a sustainable pest management strategy that relies on biocontrol. In any ecosystem, whether managed by man or not, there always will be outbreaks of pests. Resilience in the biocontrol community will allow that pest to be controlled through episodic disruptive tactics without long-term disruption of biocontrol within the ecosystem.

SUSTAINABLE BIOCONTROL METHODS IN ORCHARDS

Many tactics are available for developing a strategy for sustainable biocontrol in orchards. The basic needs are to provide adequate food, alternative hosts, shelter, and habitat for the natural enemies. Some of the characteristics of the orchard ecosystem help to provide for these essential needs and allow for the use of some tactics that are not possible in annual crops. Perennial plants can be planted in the orchard because of the temporal stability of orchards, thus requiring fewer inputs for preparing seed beds and replanting each year. Intercropping is also possible, especially in the early years before apples produce a marketable crop, thus allowing harvest of a second crop between tree rows that would not interfere with the fruit crop (Yan *et al.* 1997). The architectural complexity also provides opportunities such as adding bird nesting structures or predatory insect shelters in the trees (e.g., Carroll and Hoyt 1984; Horton *et al.* 2002). Importation of natural enemies to control pests in orchards has been used in apple (LeRoux 1971) and can lead to sustainable biocontrol but caution must be used to avoid introducing species that could disrupt natural biocontrol of other pests (Simberloff and Stiling 1996). Application of food sprays to attract natural enemies has been investigated in other crops (Hagen *et al.* 1970) but has not been well researched in orchards (Hoyt and Burts 1974). Here, follows a review of recent research that has been done in apple orchards to provide for more sustainable biocontrol. The tactics most studied have been the use of companion plants, windbreaks, compost and other mulches, and interplanting.

Companion plants

Companion plants are used within a crop for the purpose of attracting beneficial organisms with no other economic value. Flowering plants tend to have the most value in attracting biocontrol into orchards and other crop systems because they provide nectar, pollen, other habitat requirements, alternate hosts and other alternate food. Bugg and Waddington (1994) provided a review of companion plant research in orchards. Their review revealed many gaps in our knowledge on how companion plants and other cover crops in orchards affect the interactions between pests, natural enemies and the orchard trees. Many of these knowledge gaps still exist.

There were early reports of greater biocontrol of various orchard pests where flowering plants were found as compared with orchards without flowers (Peterson 1926; Leius 1967). In experimental trials it has been difficult to document higher rates of biocontrol in response to companion plants. Altieri and Schmidt (1985) showed that there were higher numbers of natural enemies and in some cases lower fruit damage from codling moth (*Cydia pomonella*) and fewer pests. They attributed the reduction in pests to the provision of alternate food and habitat in the companion planting. In New Zealand greater parasitism of tortricid pests was found in orchards with buckwheat as a companion plant than in herbicide-treated orchards (Stephens *et al.* 1998). In an experiment with strips of native flowering plants in Switzerland there were higher numbers of natural enemies than in an orchard without flowers but there was no detectable increase in biocontrol (Wyss 1996). It was shown that biocontrol was enhanced on apple and pear on potted plants among flowers compared with bare ground, but it was not demonstrated in similar treatments in orchards in the United Kingdom (Fitzgerald and Solomon 2004). Bostanian *et al.* (2004) converted one-third of an orchard to companion plants and were able to show an increase in natural enemies and after 5 years attained a level of more than 90% clean fruit; however, rates of biocontrol were not measured. Biocontrol of mites in apple orchards has been enhanced with broadleaf plants in orchards (Alston 1994), but in other studies there has been either no effect or an increase in phytophagous mites (Coli *et al.* 1994; Nyrop *et al.* 1994). In all these studies insecticides were not used in the orchards with companion plants so as not to negate any effect of the natural enemies that were attracted.

From 1992 to 1994 a multinational experiment was conducted to test the use of companion plants and selective insecticides in apple production (Brown *et al.* 1997a). Selective insecticides were chosen based on efficacy against targeted pests and benign effects on beneficial insects and mites. Field studies in the USA were in a newly planted orchard and in Poland, Czech Republic, Hungary and Romania the studies were done in mature apple orchards converted from chemically-based management. Four species of companion plants, or mixes of companion plants, were selected for use in each orchard. Species were chosen in each country based on local climate and availability of seed. The companion plants were seeded under the tree canopy in what is normally the herbicide strip (**Fig. 1**). In the US experimental plantings there was a bare strip, maintained with herbicide, 0.5 m wide centered on the center line of the tree row. Companion strips were 1.0 m wide extending from the edge of the herbicide strip and the grass alley on both sides of the tree row. The grass alleys were 2.5 m wide (**Fig. 1**). Tree spacing and cultivar selection was done separately for each country based on local conditions and standard horticultural practices.

Although specifics in the pest management program differed among countries due to regional differences, similar results were found in all trials. Numbers of natural enemies were higher in plots with companion plants and selective insecticides as compared with the standard chemical management (Brown *et al.* 1997a; Jenser *et al.* 1997). There were also lower populations of several secondary pests such as mites (Brown *et al.* 1997b; Kocourek and Tlustá 1997; Niemczyk 1997), aphids (Brown *et al.* 1997b), leafrollers (Jenser *et al.* 1997) and leafminers (Jenser *et al.* 1999). This study also showed that the amount of fruit damage by insects was similar in the biocontrol plots as in chemically managed plots (Brown *et al.* 1997a) but costs were higher due to the expense of selective chemicals and the labor involved in establishing the companion plants.

Experiments with companion plantings were continued in West Virginia, USA. Continuing research on the young orchard studied by Brown *et al.* (1997b) demonstrated no difference in insect damage to fruit comparing an orchard receiving 5 organo-phosphate insecticides with an orchard with companion plants and 2 applications of *Bacillus thuringiensis* (Brown and Glenn 1999). The companion plants used in this experiment were buckwheat (*Fagopyrum esculentum*), dill (*Anethum graveolens*), dwarf sorghum (*Sorghum bicolor*) and brassica (*Brassica napus*) planted in the same arrangement depicted in **Fig. 1**. There was, however, lower yield of fruit in the companion plant orchard due to competition for water and nutrients because the companion plants were grown under the canopy of the apple trees (Brown and Glenn 1999). As with most other studies, the use of companion plants showed promise but more research is needed to incorporate their use with other orchard practices to achieve economic sustainability for commercial implementation.

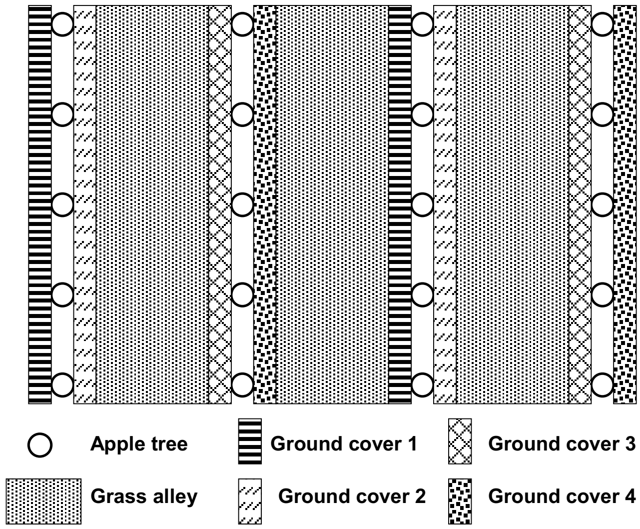

Fig. 1 Apple orchard layout used to examine four annual plant species as companion plants for sustainable biocontrol of insects. (Based on Brown *et al.* 1997b; Brown and Glenn 1999).

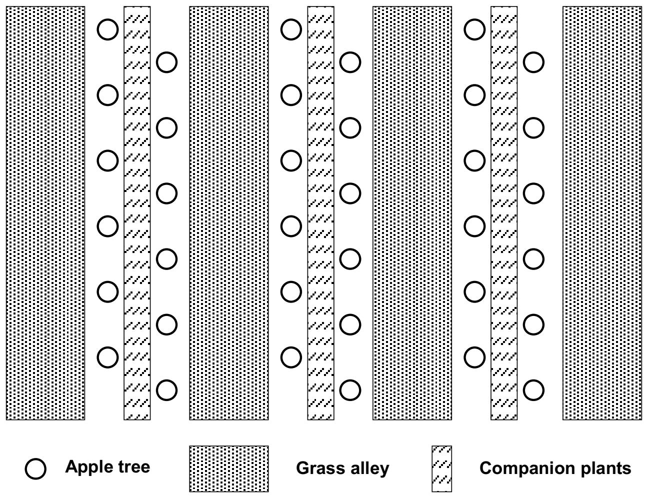

Fig. 2 Proposed apple orchard planting design to include companion plants for sustainable biocontrol. (After Brown and Mathews 2005).

A novel planting design was proposed (**Fig. 2**) with alternating rows of standard and narrow width (Brown and Mathews 2005). The orchard would have a traditional width grass alley between every other tree row. Alternate narrow alleys between tree rows would be planted with companion plants. Any necessary pesticide applications, weed control activities, compost application, and other management could be performed to both tree rows from the traditional width allies. The offset planting of the trees in adjacent rows would allow for spray treatments to cover both sides of each tree row effectively. Trees within a row would be spaced slightly farther apart than in common practice to enhance spray coverage between rows, but the overall tree density would be the same because there would be more rows per hectare due to every other alley being narrower than a conventional orchard. For example, a spacing of 2.5 m between trees in a row and 5 m between rows would result in 800 trees per ha. If the orchard in **Fig. 2** would have 3.0 m between trees in a row, a grass alley width of 5 m and a companion strip width of 3.0 m would result in 833 trees per ha, thereby not reducing potential yield.

It is very important to select the proper companion plants to fit the regional conditions and the pests that are being targeted for biocontrol. Selection criteria must include the ability to germinate and grow well under local conditions, produce flowers or other attractive resources available to biocontrol agents, produce these resources at a time when biocontrol is needed, and not attract pests into the orchard. Flowers must have the proper physical structure to allow parasitoids and predators access to pollen and nectar (Patt *et al*. 1997; Wäckers 2004). Selection of plants that attract orchard pests could result in serious damage to fruit, such as when using plants that are hosts of the tarnished plant bug, *Lygus lineolaris* (Hardman *et al.* 2004). In my own studies I found that buckwheat, dill and marigold (*Tagetes erecta*) were the best combination of annual plants for West Virginia, USA (Brown 2001b). The combination of these three plants provided flowers from mid-June until the first hard freeze, thus providing pollen and nectar for most of the time when biocontrol in apple is needed. Not only were these three plants highly attractive to insect natural enemies but the natural enemies readily foraged for aphids and tortricid (Lepidoptera) pests in potted trees placed in 10 by 10 m plots of flowers. Finally, these three species had good germination rates, grew fast and competed well with weeds under natural orchard conditions. Annuals were selected as companion plants because that although perennial plants would fit well into the orchard ecosystem the annual preparation of seed beds would inhibit the establishment of problematic perennial weeds that would affect orchard productivity.

Windbreaks

Windbreaks and hedges around orchards have the potential to contribute to biocontrol of orchards through the same mechanisms as companion plants. They also have the potential to enhance pest populations. Windbreaks contribute natural enemies, or pests, in part by the deposit of airborne arthropods on the leeward side of the hedge (Lewis and Dibley 1970). Selection of the proper species for windbreaks is critical to have the optimal match for providing natural enemies for the pests in the orchard (Solomon 1981; Tuovinen 1994; Rieux *et al*. 1999). Hedgerows have been shown to be especially useful for biocontrol of mites (Solomon 1981; Tuovinen 1994) and pear psylla in pear orchards (Solomon 1981; Rieux *et al*. 1999). A limitation in the suitability of windbreaks and hedgerows is that the effect of biocontrol enhancement may not penetrate the entire orchard. As with natural habitats, there is a limit to the distance that natural enemies can disperse (Miliczky and Horton 2005).

Mulches

Compost is known to be beneficial for improving soil organic matter, numerous other properties of soil and early tree growth (Autio and Greene 1991; Glover *et al*. 2000). When used as mulch, compost can also contribute to sustainable biocontrol of insect and weed pests. In a study on newly planted apple trees Mathews *et al*. (2002) showed that the abundance of the detritivore trophic level and ground-dwelling predators were increased with the use of composted poultry manure. However, predation of codling moth larvae was higher in the herbicide treated control plots than in the mulch (Mathews *et al*. 2004). Miñarro and Dapena (2003) also found more predatory ground beetles in herbicide treated plots than on plots mulched with plastic, straw or pine bark. When manipulating the soil surface to enhance biocontrol, the preferred foraging surface texture must be considered in addition to the enhancement of the overall detritus-based food web (Mathews *et al.* 2004).

A mulch of composted poultry manure in a mature apple orchard reduced the number of two insect pests: spotted tentiform leafminer (*Phyllonorycter blancardella*) and woolly apple aphid (*Eriosoma lanigerum*) (Brown and Tworkoski 2004). The control of the leafminer could have been due to the increased abundance of ground-dwelling predators or by increased rate of deterioration of fallen leaves over the winter in which the leafminer pupae diapause. The reduced number of woolly apple aphids, which live on apple tree roots, could also have been a result of higher levels of biocontrol or an avoidance of the friable compost surface texture (Damavandian 1999). This study also showed a direct effect of the herbicide glyphosate in reducing the abundance of insect predators (Brown and Tworkoski 2004). An interesting synergistic effect on the ratio of predators to herbivores was found when compost mulch was used in the absence of herbicides (Brown and Tworkoski 2006). The ratio of predators to herbivores was suggested as a useful index on sustainability of biocontrol. The use of composted animal waste as a mulch in apple orchards could greatly add to the sustainability of biocontrol where available, but care must be taken not to add too much phosphorus to the soil (Preusch and Tworkoski 2003).

Other orchard floor management operations also have an impact on natural enemies in the orchard ecosystem. Reducing mowing from two or three times a month to once a month or less increased the number of predators and parasitoids in the grass strips between trees and the number of spiders and predatory mirids in the tree canopy (Horton *et al*. 2003). This essentially has the same effect as adding companion plants because reduced mowing led to a more diverse plant community in the orchard ground cover and more flowers. As with companion plants care must be taken not to increase pest levels because this study showed an increase in *Lygus* spp., serious pests of tree fruit. Manipulating the orchard floor environment has much unrealized potential to modify the entire orchard ecosystem food web to increase sustainability of biocontrol of apple pests (Mathews *et al*. 2002; Brown and Tworkoski 2006).

Interplanting

Interplanting more than one fruit tree species in an orchard is another tactic for increasing plant diversity to provide for more sustainable biocontrol. Many species of *Prunus*, such as peach (*P. persica*) and cherry (*P. avium*), have extrafloral nectar glands on the leaves and petioles that provide essential nutrition for beneficial insects. In peach orchards with extrafloral nectar glands there was greater biocontrol of the oriental fruit moth (*Grapholita molesta*) than in peach orchards without extrafloral nectar (Mathews *et al.* 2007). Predatory lacewings (*Chrysoperla plorabunda*) remained active in almond (*P. amygdalus*) if they fed on nectar (Limburg and Rosenheim 2001). The parasitoid, *Trichogramma minutum*, parasitized more hosts when fed peach nectar (Shearer and Atanassov 2004). In an interplanted orchard with apple, peach and cherry trees there was a greater abundance and diversity of predatory insects on apple in an interplanted orchard than on apple in orchards without interplanting (Brown and Schmitt 2001). These findings of biocontrol enhancement in the presence of extrafloral nectar and the increase in foraging on apple trees interplanted with nectar-producing trees led us to investigate the possibility of increasing biocontrol by interplanting peach trees into an apple orchard (Brown and Mathews 2005).

Biocontrol of rosy apple aphid, *Dysaphis plantaginea*, in orchards with 9% and 50% interplanted peach trees compared with an apple monoculture was examined to test for an effect of interplanting. The presence of a low density of peach trees had no effect on biocontrol of this aphid but in orchards with 50% peach the biocontrol was significantly lower than in the apple monoculture (Brown and Mathews 2007). This result confirmed a laboratory experiment in which the presence of peach twigs producing extrafloral nectar reduced the feeding of the lady beetle (*Harmonia axyridis*) on spirea aphid (*Aphis spiraecola*) presented on apple twigs (Spellman *et al*. 2006). The presence of many nectar sources in the orchard disrupts biocontrol of aphids by *H. axyridis* through either satiation of the predator or inhibiting the ability of the predator to find aphids in the milieu of numerous sources of food within the orchard.

In the same orchards that were studied for rosy apple aphid, biocontrol of spirea aphid was not affected by the presence of peach trees at any density (Brown and Mathews

2008). However, in a study using potted peach trees in the center of an apple orchard, there was greater biocontrol of spirea aphid on apple trees immediately adjacent to the potted peach trees than on more distant apple trees (Brown and Mathews 2008). In the same study there was no affect of peach trees, either interplanted or with potted trees, on rates of parasitism for tufted apple budmoth (*Platynota idaeusalis*) (Brown and Mathews unpublished data).

The presence of extrafloral nectar has an effect of increasing the abundance of natural enemies in an orchard, but it has been difficult to show increases in rates of biocontrol. Interplanting peach trees into apple orchards may have a role in increasing sustainability of biocontrol, but implementation of this tactic has yet to be achieved.

BIOCONTROL AS AN ECOSYSTEM SERVICE

Biocontrol is an ecosystem service provided by the orchard ecosystem as a whole and not just by one component (Robertson and Swinton 2005; Losey and Vaughan 2006). The biodiversity of plants and animals, from the rhizosphere of the orchard to surrounding habitats, contributes to the level of biological regulation, including biocontrol, inherent in the ecosystem (Altieri 1999). As stated earlier, temporal stability helps to develop sustainable biocontrol in orchards. All the various components of the ecosystem and surrounding habitats that support colonists to the orchard interact to sustain the community of natural enemies of insects and other pests (Boller *et al*. 2004). Temporal stability of orchards also permits the evolution of the biocontrol community over time. Immigration from the surrounding species pool into a stable agroecosystem takes time to develop fully the biocontrol service provided by the system. Sustainable approaches to orchard production have shown that it takes several years for damage levels of fruit to stabilize at an acceptable level (Prokopy 2003; Bostanian *et al.* 2004).

Although some of the studies reviewed in this study documented higher rates of biocontrol as a result of ecosystem management practices (e.g., Stephens *et al*. 1998) many were only able to infer greater biocontrol as the most likely cause for reduced pest populations (Wyss 1996; Brown and Glenn 1999; Jenser *et al.* 1999). As an emergent property of the orchard ecosystem, detecting biocontrol of specific pests within the milieu of all the natural variation inherent in ecosystem level experiments may not be possible in many studies. Proper evaluation of sustainable biocontrol practices will need holistic approaches of research rather than the more typical reductionist approaches. The reductionist method of teasing apart independent causes and effects may not be capable of detecting the true strength of ecosystem services. Manipulating one or a few variables in the ecosystem does not allow for testing the effects of the whole ecosystem with its multitude of interactions. What is needed are more studies that examine ecosystem management concepts replicated across widely different environmental conditions (e.g., Brown *et al*. 1997a) instead of replications of identical treatments under similar conditions.

CONCLUSION

The studies reviewed here show that there is a large potential for sustainable biocontrol in orchards. The next step in research is to integrate two or more of the methods described to redesign the orchard ecosystem to optimize biocontrol with all other inputs into the orchard (Hill *et al.* 1999). Not all of the methods for enhancing biocontrol in orchards may be compatible and what works under one set of environmental conditions may not work in another. Differences in climate, diversity of surrounding habitats, pest complex and local economics need to be considered when selecting the appropriate tactics for optimizing biocontrol. Direct pests of fruit do considerable damage in small numbers and will not be controlled adequately by biocontrol alone. Such pests will require additional control methods such as behavioral tactics (e.g., mating disruption, attract and kill, trapping), host plant resistance, or selective insecticides. Integration of sustainable biocontrol with other pest control methods and all other horticultural methods will need to be optimized for successful development of an overall sustainable orchard production system.

ACKNOWLEDGEMENTS

I thank Roberta Bisignano for valuable comments on an earlier draft of this review.

REFERENCES

Alston DG (1994) Effect of apple orchard floor vegetation on density and dispersal of phytophagous and predaceous mites in Utah. *Agriculture Ecosystems and Environment* **50**, 73-84

Altieri MA (1999) The ecological role of biodiversity in agroecosystem. *Agriculture Ecosystems and Environment* **74**, 19-31

Altieri MA, Schmidt LL (1985) Cover crop manipulation in northern California orchards and vineyards: effects on arthropod communities. *Biological Agriculture and Horticulture* **3**, 1-24

Autio WR, Greene DW (1991) Improving the growth of newly planted apple trees. *HortScience* **26**, 840-843

Boller EF, Häni F, Poehling HM (2004) *Ecological Infrastructure: Ideabook on Functional Biodiversity at the Farm Level*, IOBC, Mattenbach AG, Winterthur, Switzerland, 212 pp

Bostania NJ, Goulet H, O'Hara J, Masner L, Racette G (2004) Towards insecticide free apple orchards: flowering plants to attract beneficial arthropods. *Biocontrol Science and Technology* **14**, 25-37

Brown MW (1993) Resilience of the natural arthropod community on apple to external disturbance. *Ecological Entomology* **18**, 169-183

Brown MW (1999) Applying principles of community ecology to pest management in orchards. *Agriculture Ecosystems and Environment* **73**, 103-106

Brown MW (2001a) Functional biodiversity and agro-ecosystem management: 2. role in integrated fruit production. *IOBC/WPRS Bulletin* **24 (5)**, 5-11

Brown MW (2001b) Flowering ground cover plants for pest management in peach and apple orchards. *IOBC/WPRS Bulletin* **24 (5)**, 379-382

Brown MW, Adler CRL (1989) Community structure of phytophagous arthropods on apple. *Environmental Entomology* **18**, 600-607

Brown MW, Glenn DM (1999) Ground cover plants and selective insecticides as pest management tools in apple orchards. *Journal of Economic Entomology* **92**, 899-905

Brown MW, Mathews CR (2005) Components of an ecologically and economically sustainable orchard. *IOBC/WPRS Buletin* **28 (7)**, 73-76

Brown MW, Mathews CR (2007) Conservation biological control of rosy apple aphid, *Dysaphis plantaginea* (Passerini), in eastern North America. *Environmental Entomology* **36**, 1131-1139

Brown MW, Mathews CR (2008) Conservation biological control of spirea aphid, *Aphis spiraecola* (Hemiptera: Aphididae) on apple by providing natural alternative food resources. *European Journal of Entomology* **105**, 537-540

Brown MW, Schmitt JJ (2001) Seasonal and diurnal dynamics of beneficial insect populations in apple orchards under different management intensity. *Environmental Entomology* **30**, 415-424

Brown MW, Tworkoski T (2004) Pest management benefits of compost mulch in apple orchards. *Agriculture Ecosystems and Environment* **103**, 465-472

Brown MW, Tworkoski T (2006) Enhancing biocontrol in orchards by increasing food web biodiversity. *Journal of Fruit and Ornamental Plant Protection* **14 (3)**, 19-27

Brown MW, Welker WV (1992) Development of the phytophagous arthropod community on apple as affected by orchard management. *Environmental Entomology* **21**, 485-492

Brown MW, Niemczyk E, Baicu T, Balázs K, Jarošík V, Jenser G, Kocourek F, Olszak R, Serboiu A, Van der Zwet T (1997a) Enhanced biological control in apple orchards using ground covers and selective insecticides: an international study. *Horticultural Science (Prague)* **24**, 35-37

Brown MW, van der Zwet T, Glenn DM (1997b) Impact of ground cover plants on pest management in West Virginia, USA, apple orchards. *Horticultural Science (Prague)* **24**, 39-44

Bugg RL, Waddington C (1994) Using cover crops to manage arthropod pests of orchards: a review. *Agriculture Ecosystems and Environment* **50**, 11-28

Carroll DP, Hoyt SC (1984) Augmentation of European earwigs (Dermaptera: Forficulidae) for biological control of apple aphid (Homoptera: Aphididae) in an apple orchard. *Journal of Economic Entomology* **77**, 738-740

Coli WM, Ciurlino RA, Hosmer T (1994) Effect of understory and border vegetation composition on phytophagous and predatory mites in Massachusetts commercial apple orchards. *Agriculture Ecosystems and Environment* **50**, 49-60

Damavandian MR (1999) Biology of subterranean populations of woolly apple aphid, *Eriosoma lanigerum* (Hausmann) (Homoptera: Aphididae), in apple orchards. PhD Dissertation, Department of Entomology and Nematology, University of Stellenbosch, South Africa, 119 pp

Fitzgerald JD and Solomon MG (2004) Can flowering plants enhance numbers of beneficial arthropods in UK apple andpear orchards? *Biocontrol Science and Technology* **14**, 291-300

Glover JD, Reganold JP, Andrews PK (2000) Systematic methods for rating soil quality of conventional, organic, and integrated apple orchards in Washington State. *Agriculture Ecosystems and Environment* **80**, 29-45

Hagen KS, Sawall EF, Tassan RL (1970) The use of food sprays to increase effectiveness of entomophagous insects. *Proceedings of Tall Timbers Conference on Ecological Animal Control and Habitat Management* **2**, 59-82

Hardman JM., Jensen KIN, Moreau DL, Franklin JL, Bent ED (2004) Effects of ground cover treatments and insecticide use on population density and damage caused by *Lygus lineolaris* (Heteroptera: Miridae) in apple orchards. *Journal of Economic Entomology* **97**, 993-1002

Hill SB, Vincent C, Chouinard G (1999) Evolving ecosystems approachs to fruit insect pest management. *Agriculture Ecosystems and Environment* **73**, 107-110

Horton DR, Broers DA, Hinojosa T, Lewis M, Miliczky ER, Lewis RR (2002) Diversity and phenology of predatory arthropods overwintering in cardboard bands placed in pear and apple orchards of central Washington state. *Annals of the Entomological Society of America* **95**, 469-480

Horton, DR, Broers DA, Lewis RR, Granatstein D, Zack RS, Unruh TR, Moldenke AR, Brown JJ (2003) Effects of mowing frequency on densities of natural enemies in three pacific northwest pear orchards. *Entomologia Experimentalis et Applicata* **106**, 135-145

Hoyt SC, Burts EC (1974) Integrated control of fruit pests. *Annual Review of Entomology* **19**, 231-252

Jenser G, Balázs K, Erdélyi CS, Haltrich A, Kozár F, Markó V, Rácz V, Samu F (1997) The effect of an integrated pest management program on the arthropod populations in a Hungarian apple orchard. *Horticultural Science (Prague)* **24**, 63-76

Jenser G, Balázs K, Erdélyi CS, Haltrich A, Kozár F, Markó V, Rácz V, Samu F (1999) Changes in arthropod population composition in IPM apple orchards under continental climatic conditions in Hungary. *Agriculture Ecosystems and Environment* **73**, 141-154

Kocourek F, Tlustá S (1997) The management of *Panonychus ulmi* and *Tetranychus urticae* populations by *Typhlodromus pyri* predator mites in apple orchards. *Horticultural Science (Prague)* **24**, 76-82

Leius K (1967) Influence of wild flowers on parasitism of tent caterpillar and codling moth. *Canadian Entomologist* **94**, 444-446

LeRoux EJ (1971) Biological control attempts on pome fruit (apple and pear) in North America, 1860-1970. *Canadian Entomol*ogist **103**, 963-974

Lewis T, Dibley GC (1970) Air movement near windbreaks and a hypothesis of the mechanism of the accumulation of airborne insects. *Annals of Applied Biology* **66**, 477-484

Lewis WJ, Van Lenteren JC, Phatak SC, Tumlinson JC (1997) A total system approach to sustainable pest management. *Proceedings of the National Academy of Sciences USA* **94**, 12243-12248

Limburg DD, Rosenheim JJ (2001) Extrafloral nectar consumption and its influence on survival and development of an omnivorous predator, larval *Chrysoperla plorabunda* (Neuroptera: Chrysopidae). *Environmental Entomology* **30**, 595-604

Losey JE, Vaughan M (2006) The economic value of ecological services provided by insects. *BioScience* **56**, 311-323

MacArthur RH, Wilson EO (1963) An equilibrium theory of insular zoogeography. *Evolution* **17**, 373-387

Mathews CR, Bottrell DG, Brown MW (2002) A comparison of conventional and alternative understory management practices for apple production: multitrophic effects. *Applied Soil Ecol*ogy **21**, 221-231

Mathews CR, Bottrell DG, Brown MW (2004) Habitat manipulation of the apple orchard floor to increase ground-dwelling predators and predation of *Cydia pomonella* (L.) (Lepidoptera: Tortricidae). *Biological Control* **30**, 265-273

Mathews CR, Brown MW, Bottrell DG (2007) Leaf extrafloral nectaries enhance biological control of a key economic pest, *Grapholita molesta* (Lepidoptera: Tortricidae), in peach (Rosales: Rosaceae). *Environmental Entomology* **36**, 383-389

Mészáros Z (Ed) (1984) Results of faunistical and floristical studies in Hungarian apple orchards. *Acta Phytopathologica Academiae Scientiarum Hungaricae* **19**, 91-176

Miliczky ER, Horton DR (2005) Densities of beneficial arthropods within pear and apple orchards affected by distance from adjacent native habitat and association of natural enemies with extra-orchard host plants. *Biological Control* **33**, 249-259

Miñarro M, Dapena E (2003) Effects of groundcover management on ground beetles (Coleoptera: Carabidae) in an apple orchard. *Applied Soil Ecology* **23**, 111-117

Niemczyk E (1997) The occurrence of different groups of phytophagous and predatory mites on apple plots sprayed according to different programs. *Horticultural Science (Prague)* **24**, 45-52

Nyrop JP, Minns JC, Herring CP (1994) Influence of ground cover on dynamics of *Amblyseius fallacis* Garman (Acarina: Phytoseiidae) in New York apple orchards. *Agriculture Ecosystems and Environment* **50**, 61-72

Patt JM, Hamilton GC Lashomb JH (1997) Foraging success of parasitoid wasps on flowers: interplay of insect morphology, floral architecture and searching behavior. *Entomologia Experimentalis et Applicata* **83**, 21-30

Peterson A (1926) Oriental fruit moth damage in cultivated and uncultivated orchards. *Proceedings of Annual Meeting New Jersey State Horticultural Society* **3**, 83-86

Pickett AD, Patterson NA (1953) The influence of spray programs on the fauna of apple orchards in Nova Scotia. IV. a review. *Canadian Entomologist* **85**, 472-478

Pickett AD, Putman WL, LeRoux EJ (1956) Progress in harmonizing biological and chemical control of orchard pests in eastern Canada. *Proceedings of the 10th International Congress of Entomology* **3**, 169-174

Preusch PL, Tworkoski TJ (2003) Nitrogen and phosphorus availability and weed suppression from composted poultry litter applied as mulch in a peach orchard. *HortScience* **38**, 1108-1111

Prokopy RJ (2003) Two decades of bottom-up ecologically based pest management in a small commercial apple orchard in Massachusetts. *Agriculture Ecosystems and Environment* **94**, 299-309

Rathman RJ, Brunner JF (1988) Abundance and composition of predators on young apple, *Malus domestica* Borkhausen, within sagebrush and riparian species pools in north central Washington. *Melanderia* **46**, 65-81

Rieux R, Simon S, Defrance H (1999) Role of hedgerows and ground cover management on arthropod populations in pear orchards. *Agriculture Ecosystems and Environment* **73**, 119-127

Robertson GP, Swinton SM (2005) Reconciling agricultural productivity and environmental integrity: a grand challenge for agriculture. *Frontiers in Ecology and the Environment* **3**, 38-46

Sansavini S (1997) Integrated fruit production in Europe: research and strategies for a sustainable industry. *Scientia Horticulturae* **68**, 25-36

Shearer PW, Atanassov A (2004) Impact of peach extrafloral nectar on key biological characteristics of *Trichogramma minutum* (Hymenoptera: Trichogrammatidae). *Journal of Economic Entomology* **97**, 789-792

Simberloff D, Stiling P (1996) How risky is biological control? *Ecology* **77**, 1965-1974

Slingerland MV, Crosby CR (1914) *Manual of Fruit Insects*, Macmillan, New York, 503 pp

Solomon MG (1981) Windbreaks as a source of orchard pests and predators. In: Thresh JM (Ed) *Pests, Pathogens, and Vegetation: the Role of Weeds and Wild Plants in the Ecology of Crop Pests and Diseases*, Pitman Advanced Pub., Boston, pp 273-283

Southwood TRE (1961) The number of species of insect associated with various trees. *Journal of Animal Ecology* **30**, 1-8

Southwood TRE (1977) The relevance of population dynamic theory to pest status. In: Cherrett JM, Sagar GR (Eds) *Origins of Pest, Parasite, Disease, and Weed Problems*, 18th Symposium of the British Ecological Society, Blackwell Science, London, pp 35-54

Spellman B, Brown MW, Mathews CR (2006) Effect of floral and extrafloral resources on predation of *Aphis spiraecola* by *Harmonia axyridis* on apple. *BioControl* **51**, 715-724

Stephens MJ, France CM, Wratten SD, Frampton C (1998) Enhancing biological control of leafrollers (Lepidoptera: Tortricidae) by sowing buckwheat (*Fagopyrum esculentum*) in an orchard. *Biocontrol Science and Technology* **8**, 547-558

Strickler K, Whalon M (1985) Microlepidoptera species composition in Michigan apple orchards. *Environmental Entomology* **14**, 486-495

Szentkirályi F, Kozár F (1991) How many species are there in apple insect communities?: testing the resource diversity and intermediate disturbance hypotheses. *Ecological Entomology* **16**, 491-503

Tuovinen T (1994) Influence of surrounding trees and bushes on the phytoseiid mite fauna on apple orchard trees in Finland. *Agriculture Ecosystems and Environment* **50**, 39-47

Wäckers FL (2004) Assessing the suitability of flowering herbs as parasitoid food sources: flower attractiveness and nectar accessibility. *Biological Control* **29**, 307-314

Whalon ME, Croft BA (1986) Immigration and colonization of portable apple trees by arthropod pests and their natural enemies. *Crop Protection* **5**, 376-384

Wyss E (1996) The effects of artificial weed strips on diversity and abundance of the arthropod fauna in a Swiss experimental apple orchard. *Agriculture Ecosystems and Environment* **60**, 47-59

Yan Y-H, Yu Y, Du X-G, Zhao B-G (1997) Conservation and augmentation of natural enemies in pest management of Chinese apple orchards, *Agriculture Ecosystems and Environment* **62**, 253-260