

CULTURAL MANIPULATIONS TO ENHANCE BIOLOGICAL CONTROL IN AUSTRALIA AND NEW ZEALAND: PROGRESS AND PROSPECTS

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ABSTRACT

Increasing social and government awareness of ecosystem services has facilitated a significant increase in conservation biological control (CBC) research in Australasia. Coupled with the recent development of new methods and theoretical insights, this is an exciting period for the discipline of CBC. Increasingly, this branch of arthropod biocontrol is taking a rigorous, directed approach, 'ecological engineering', rather than relying on a crude approximation that diversifying vegetation in a 'shotgun' manner will tend to reduce pest numbers. Funding agencies are supporting such work in several agricultural systems. Industry too has become an important supporter of such work, especially in New Zealand. This paper will review conservation biological control work in Australasia to illustrate the ecological engineering approach and prospects for wider adoption of conservation biological control.

INTRODUCTION

Ecosystem services (ES) such as nutrient cycling, pollination and biological control support agricultural production. Costanza *et al.* (1997) calculated the total ES value for the world at US\$ 55 trillion per year, the annual gross global production is in contrast only US\$18 trillion.

Many current pest and disease problems are the result of a disruption of the restraints formerly imposed by ES. More than 40% of all world food production is being lost to insect pests (15%), plant pathogens (13%) and weeds (12%). 3 billion kilograms of pesticides are currently used each year to ensure food production, but there is no evidence that this use has led to sustainable pest population reductions (Pimentel 2004). Continued reliance on frequent, high-rate use of artificial inputs is ineffective and unsustainable. Problems associated with that approach include pesticide resistance and suppression of natural enemies like parasitoids and predators (Theiling and Croft 1988). Further, because only an estimated 0.1% of the 3 billion kilograms of the formulated product applied each year actually reaches the target

organisms, a large proportion is available in the environment to affect non-target species (Metcalf 1994). Demographic studies have shown repeatedly that natural enemies like predators and parasitoids inflict the largest proportion of insect herbivores' mortality, when compared with other factors such as competition, weather and plant effects. Reducing reliance on pesticides by widespread implementation of integrated pest management is therefore a critical objective for 21st century agriculture. Biological control is an extremely important alternative to widespread pesticide use and one of its most promising components is the conservation of natural enemies.

Conservation biological control (CBC) involves the provision of resource subsidies (Polis and Strong 1996) such as pollen, nectar, shelter and/or alternative prey or hosts for predators and parasitoids. However, the complexities inherent in any plant-pest-beneficial system require detailed understanding through theoretical and empirical analyses before CBC measures can be implemented in a rational manner. It is not enough merely to observe direct, "beneficial" predator-prey or parasitoid-host interactions and to attempt to recreate them in agricultural settings. The mechanisms driving these interactions, and their indirect effects on other organisms, should be elucidated to confirm that a CBC program is both effective and environmentally responsible (e.g., Berryman 1999; Ehler 1994; Gurr and Wratten 1999; Kareiva 1996; Landis *et al.* 2000; Simberloff and Stiling 1996; Strong and Pemberton 2001; Waage 1990).

ECOLOGICAL PRINCIPLES

Two main ecological principles are at the heart of natural enemy enhancement by floral foods. The first is the concept of life-history omnivory, whereby a species feeds at different trophic levels during different life-history stages (Polis and Strong 1996). Many natural enemies, for example certain parasitoids, lacewings, and hoverflies, are carnivorous during their larval stage and become herbivorous as adults. This ecological phenomenon undermines the concept of discrete trophic-level paradigm and replaced it with complex multispecies food webs and interaction webs (e.g., Hawkins 1992; Janssen *et al.* 1998; Polis and Strong 1996). It is the seemingly minor interactions with non-host or non-prey species that have been largely overlooked. Understanding these interactions not only reduces the probability of unforeseen environmental harm (e.g., Strong and Pemberton 2001), but also provides the theoretical tools necessary for successful biological control (Berryman 1999; Gurr and Wratten 1999; Janssen *et al.* 1998; Landis *et al.* 2000; Lewis *et al.* 1998).

The second component of ecological theory that is integral to CBC is that of resource subsidies. Concomitant with the breakdown of the trophic-level paradigm was the understanding that many species obtain resources from outside their target habitat. These "spatial subsidies" allow an increase in consumer abundance, beyond that which can be sustained by the resources present within the local habitat alone (Polis and Strong 1996). Analogous processes occur when natural enemies feed on non-crop plants within the crop habitat. During an outbreak of pests, their natural enemies will be constrained by the availability of other resources that may, for example be required by the adult rather than by predacious/parasitic larvae. The provision of any non-crop plant or resource, from which a natural enemy may

derive benefits, is particularly important in agricultural systems, where expansive monocultures are typical. Aggregation of natural enemies around resource-providing plants has frequently been recorded (e.g., Berndt *et al.* 2002; Hickman and Wratten 1996; Hooks *et al.* 1998; Root 1973; van Emden 1963) and several studies have shown that floral resources allow parasitoids to maximize their reproductive success via increases in longevity and egg load (e.g., Arthur 1944; Dyer and Landis 1996; Jacob and Evans 2000; Heimpel *et al.* 1997; Jervis *et al.* 1993; Wheeler 1996), and that this may lead to reduced populations of arthropod pests in the field (Irvin *et al.* 2000; Patt *et al.* 1997). Even where natural enemies do not exhibit life-history omnivory, they may be sufficiently polyphagous to use alternative diets during periods of low pest density. Habitat manipulation may provide foods such as pollen and non-pest herbivores so that communities of natural enemies may be maintained on farms until pest numbers begin to build up.

RISKS

CBC most commonly involves the enhancement of natural enemy species that are already present in the system, so assessment of the potential for host-range expansion is not imperative. Other non-target effects of conservation biological control must nonetheless be considered before floral resource subsidies can be applied responsibly to an agricultural setting. Possibly the greatest environmental threat posed by non-crop resource subsidies is the potential for exotic plant species that are introduced for CBC to become invasive (e.g., Cheesman 1998). There are also several potential indirect effects that may reduce the effectiveness of a conservation biological control program, or contribute to environmental harm. First, intraguild competition and predation may influence the success of natural enemy enhancement using floral resources. Another potential risk is the enhancement of species other than the targeted beneficials. It is reasonable to assume that while beneficials are attracted to flowers and benefit from the provided nectar and pollen, so too may predators and hyperparasitoids of the natural enemies, as well as the pests themselves. Such risks highlight the desirability of avoiding a 'shotgun approach' (*sensu* Gurr *et al.* 2005) to providing food plants but also illustrates that achieving adequate suppression of multiple pest species within a given crop system may not always be tractable. Thus, theoretical and mechanism-based approaches as well as practical guidelines are imperative if success rates of biological control are to improve.

For example, CBC approaches have to consider the complexity of ways in which flowers may affect the population dynamics of pest/beneficial systems. There is a hierarchy of levels at which floral resources may selectively favour the beneficials more than the pests and their own antagonists. Availability of resources only to a beneficial may be achieved via: the morphology of the flowers, the quality of nectar and pollen, floral attractiveness and the morphology of insects targeted. A relative advantage to the beneficial may further be provided by: a greater fitness improvement of the beneficial compared with that of the pest, a spatial or temporal difference in the foraging of beneficials and pests and the beneficial benefits from a prey/host of improved quality more than does the prey/host itself. The effectiveness of a beneficial may also be enhanced by changes in its sex ratio and a relatively greater enhancement of its fitness than that of its fourth-trophic-level antagonists.

Partial information, based on anecdote, may lead to the accidental introduction of noxious weeds, and the enhancement of pest populations (Baggen and Gurr 1998) or higher-order predators/hyperparasitoids (Stephens *et al.* 1998). Practical guidelines for employing plant foods in farming systems are therefore required. These guidelines must be based on sound theoretical and empirical foundations and incorporate the following steps (Gurr *et al.* 2005): (1) Field surveys to determine which natural enemies of the key pest are present, (2) literature review for available information on ecology of natural enemies and pests, (3) modelling to predict benefits and avoid risks, (4) consultation with farmers to determine agronomic acceptability of possible resource plants and avoid risks (e.g., weed potential, product contamination, and toxicity to livestock), (5) laboratory assays to measure the effect of candidate plant species on important natural enemy species (e.g., longevity, fecundity, and flight propensity), (6) laboratory assays to measure the effect of candidate plant resources on target pest (e.g., to avoid nectar feeding by adult Lepidoptera or foliar feeding by larvae), (7) field experiments to check for attraction of beneficials and unpredicted effects including enhancement of secondary pests or agonists of important natural enemy species. CBC approaches that incorporate theoretical and mechanism-based approaches and follow practical guidelines are likely to be more successfully and become more widely practised. Collectively, these approaches constitute the foundation for ecological engineering.

ECOLOGICAL ENGINEERING EXAMPLES

The ecological engineering approach to CBC (Gurr *et al.* 2004), is characterised by being based on ecological theory (as explored in preceding sections) and by being developed via rigorous experimentation. The process of development typically aims to identify and provide the most functional components of biodiversity, rather than simply increasing diversity in a 'shotgun' fashion. By doing so, it minimizes the risks discussed above. This directed approach to understanding and using agricultural biodiversity is important because there are a number of pitfalls in the simplistic assumption that enhanced biodiversity will suppress pests in a risk-free fashion. Essentially, ecological engineering uses a range of modern techniques to identify the 'right kind' of diversity.

An early example of CBC in Australia was the work of Baggen and Gurr (1998) that used laboratory bioassays and small scale field experiments to identify plant species suitable for enhancing the potato moth parasitoid *Copidosoma koehleri* (Fig. 1).

Figure 1. Small-scale field experiments (pictured) coupled with laboratory bioassays are an important preliminary phase before open field studies in commercial crops. (Photo: K. Waite).



Several plant species enhanced this hymenopteran parasitoid's fecundity and adult longevity but were fed upon also by the target pest, potato moth (*Phthorimaea operculella*). Use of an ecological engineering approach identified the 'selective food plant' phenomenon, whereby plant species that benefit the target natural enemy whilst denying feeding by pests. In the *Copidosoma/Phthorimaea* system, one such selective food plant was *Phacelia tanacetifolia*. Observations of floral morphology revealed that nectaries were at the base of the corolla and access to these was restricted by the presence of stamen appendages (Fig. 2a). The presence of outward pointing hairs arising from the style may also have been important in preventing the moth inserting its proboscis (Fig. 2b).

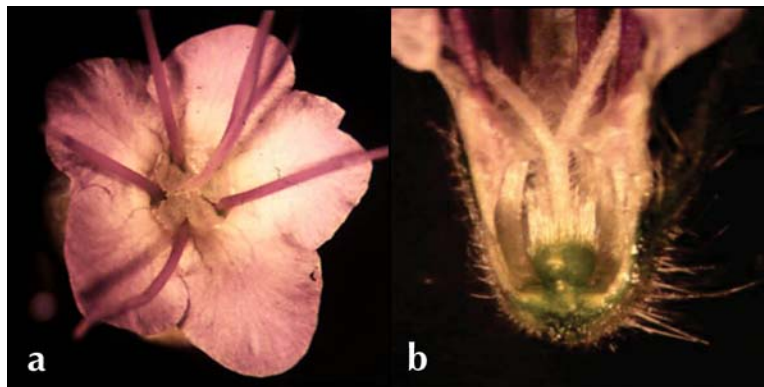


Figure 2. (a) Inflorescence of *Phacelia tanacetifolia* showing the presence of stamen appendages that block access to the nectaries and are thought to be responsible for its 'selective food plant' status (see text for explanation) (b) outward pointing hairs on style though to interfere with proboscis insertion by moths (Photos L. R. Baggen). UGA1390025, UGA1390026

Subsequent farm-scale field (Baggen *et al.* 1999) work validated the observations from smaller scale experiments and showed the value of laboratory studies in plant species selection.

Such work has led to the ecological engineering approach being used in more recent projects. The vineyard system offers especially good scope for CBC because its perennial nature affords a higher degree of stability than is common to annual crops. The vineyard 'floor' is also an important potential location for non-crop plants. Progress in this system is summarised in the following case study.

CASE STUDY: CONSERVATION BIOLOGICAL CONTROL OF PESTS IN VINEYARDS IN NEW ZEALAND AND AUSTRALIA

Biological control of insect pests in New Zealand and Australian vineyards is focused on the management of leafrollers, specifically the lightbrown apple moth (LBAM), *Epiphyas postvittana* Walker (Lepidoptera: Tortricidae) which is considered to be the most damaging

to grapevines (Nicholas *et al.* 1994; Bailey 1997). The larvae of *E. postvittana* damage grapevines by feeding on new shoots, flowers, berries, stalks and leaves (Lo and Murrell 2000). Damage is also caused by the transmission of *Botrytis cinerea* amongst grape bunches by the larvae (Bailey 1997; Nair *et al.* 1988) or by providing infection sites for the *Botrytis* fungus by larval feeding on the bunches (Nicholas *et al.* 1994). Such damage may cause significant losses in grape production; for example in New Zealand, mid-season losses, as a result of *Botrytis* infections, may exceed 20% under favourable conditions, and complete losses of crops can occur before harvest in very wet seasons (Nicholas *et al.* 1994). Currently, the most common method of control of insect pests in vineyards is via insecticides.

Though there are benefits from providing natural enemies with flowering plants, the ultimate aim of CBC is to determine whether, by adding flowering plants, the five steps in an established hierarchy of research outcomes (Gurr *et al.* 2003) are met. The hierarchy of research outcomes include:

1. Aggregation of parasitoids at or near the flowers
2. An enhancement of the parasitoids' 'fitness' (longevity, fecundity and searching efficiency)
3. An increase in parasitism rate
4. A decrease in pest populations
5. Pest populations are brought below an economic threshold

In this case study we consider the levels of success that have been achieved in this hierarchy through understorey management in vineyards in relation to managing populations of leafrollers, such as *E. postvittana* in New Zealand and Australia.

E. postvittana is attacked by a wide range of parasitoids and predators in New Zealand during most of its developmental stages (Thomas 1989). However, it is *Dolichogenidea tasmanica* (Cameron) (Hymenoptera: Braconidae) which is the most common parasitoid attacking leafroller larvae in New Zealand (Berndt 2002; Charles *et al.* 1996). In Australia, however, it is the egg parasitoid, *Trichogramma carverae* (Oatman and Pinto) (Hymenoptera: Trichogrammatidae) which is commonly used as a commercial biological control agent of *E. postvittana* (see below).

Berndt *et al.* (2002) worked on CBC to enhance natural enemy populations of *E. postvittana* in vineyards in New Zealand. In that study, the first level of the hierarchy of research outcomes (see above) was met when significantly more male *D. tasmanica* were collected on yellow sticky traps in buckwheat plots compared with control plots where no flowering plants were present (Berndt *et al.* 2002). Buckwheat did not appear to increase local adult parasitoid populations and the low numbers of parasitoids captured overall may explain this. In an earlier study, Irvin *et al.* (in press) examined the effects of buckwheat plants on *D. tasmanica* 'fitness' (longevity and fecundity) in laboratory experiments. The results showed that longevity of female *D. tasmanica* was increased from 12 days (water only) to 35 days when they were exposed to buckwheat, and that buckwheat enhanced potential fecundity by

62% (Irvin *et al.* in press); thus the second level of the hierarchy was reached. The third level was achieved when parasitism rates of leafroller larvae were increased by more than 50% in one vineyard of three when buckwheat flowers were present. At the other two vineyards, buckwheat had no effect on parasitism rates, but at these locations, leafroller populations were low, because insecticides had been used in that growing season.

Although the research described here has shown that the first three levels in the hierarchy of research outcomes can be achieved in the vineyard system, the fourth and fifth levels have not yet been demonstrated in New Zealand. Current research is addressing whether the fourth level can be achieved; however, preliminary results (Scarratt, unpublished) indicate that there is no reduction in the numbers of leafroller larvae in areas of the vineyard where buckwheat was planted. Possible reasons for this include the possibility that leafroller adults also benefit from flowering buckwheat. However, Irvin (1999) showed that *E. postvittana* larvae fed on buckwheat leaves in the laboratory but could not successfully develop to adults and that the longevity and fecundity of adult *E. postvittana* were not increased when they were provided with buckwheat. Another reason why reductions in the pest population may not have occurred when buckwheat was present may be that *E. postvittana* has a high fecundity (Danthanarayana 1975) and that *D. tasmanica* induced mortality, even via the provision of resource subsidies cannot overcome the effects of high pest fecundity. This is also thought to be the reason why predation by ladybugs (Coleoptera: Coccinellidae) may not reduce the numbers of mealybugs (Hemiptera: Pseudococcidae) (Dixon 2000). These questions associated with adding floral resources to vineyards may be usefully explored further with the support of ecological modelling (Kean *et al.* 2003).

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Recent studies in the Australian vineyard system have revealed still greater levels of complexity in plant species choice for cultural manipulations to enhance biological control. The egg parasitoid, *Trichogramma carverae*, is an important Australian endemic biocontrol agent for *E. postvittana*. Studies adult feeding by *T. carverae* showed that its longevity and realised fecundity were markedly improved by several flower species (including buckwheat as used in New Zealand to enhance other parasitoids) but there were remarkably strong within-species differences conferred by different varieties of alyssum, *Lobularia maritima* (Begum *et al.* 2004). Exposure to white flowers gave realised fecundity levels significantly in excess of those for other flower colours for three-day old adults (Fig. 3). Differences were still greater after 6 days to the extent that realised fecundity for non-white flower treatments was no greater than in the control treatment in which flowers had been removed from shoots.

A further dimension to the selective food plant syndrome explored by Begum (2004) was the ability of pest larvae to feed on the foliage of plants used in CBC. In this work on *T. carverae*, not only was *L. maritima* (white flowering variety) the optimal species for adults, larvae of the pest (*E. postvittana*) were unable to develop on its foliage. Such experimental work in the laboratory and glasshouse was important in identifying plant species to be included in larger scale field evaluations.

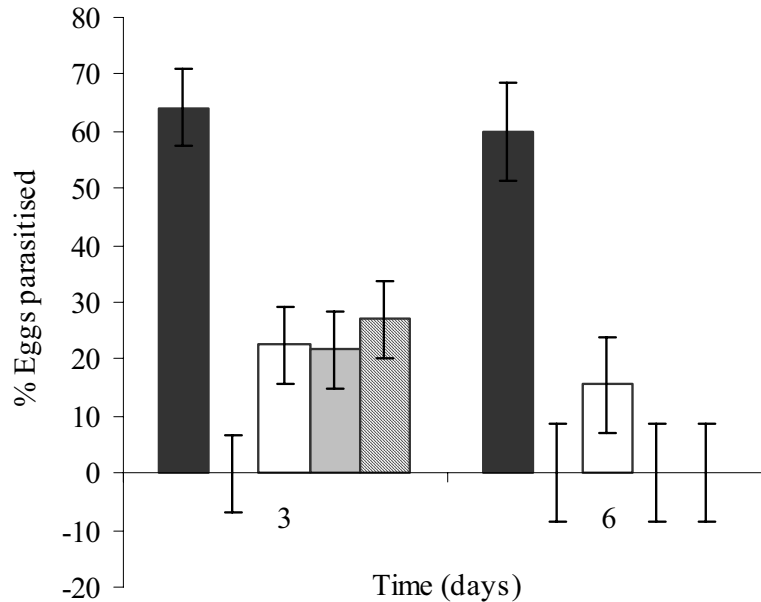


Figure 3. Parasitism of *E. postvittana* eggs by *T. carverae* is markedly affected by within-species differences in flower colour for alyssum: shaded = white flowers present, unshaded = control, white flowers removed (zero for both dates), unshaded = light pink flowers present, grey = dark pink flowers present, crosshatched = purple flowers present. (from Begum *et al.* 2004)

CONCLUSION

Cultural manipulations have to consider the broader context of agriculture, as any techniques for natural enemy enhancement that conflict with practical farming will remain solely theoretical. It is critical to recognize that farmers have the principal aim of making a profit. This objective may be tempered by secondary aims such as seeking to maximize farm sustainability and alternative income, as well as reducing risk, workload, and environmental impact. Increasing natural enemy density or impact, and even reducing the densities and impact of pests, will be significant only within this far broader frame of reference. In order for cultural manipulation techniques to be put into practice, economic requirements of farmers must be met. For example, if one-third of a crop must be replanted with non-crop floral resources before a significant level of natural enemy enhancement can be achieved, this method (irrespective of its theoretical benefits) will never be utilized. Fortunately, such levels of agronomic disruption are unlikely to be necessary, as improved pest management may require as little as 1 in 20 rows to be planted with floral resources (Grossman and Quarles 1993) or for the crop itself to provide key resources (Hossain *et al.* 1999). Essentially, farmers will be concerned with practical questions such as “what?”, “where?”, and “when?” By taking an ecological engineering approach, researchers are increasingly able to answer these queries with guidance on issues such as what food plants should be used, where they should be positioned in relation to the crop for maximum benefit, and when to sow or slash the plants to

ensure nectar and pollen are available over the desired periods. Such research will require further rigorous empirical studies as the level of interest in conservation biological control grows in farming communities. However, to fully meet the potential for food plants in pest management, the underutilized population modelling and ecological theory approaches need to be developed. This will require researchers to more consistently address the other key questions: “how?” and “why?” Developing general theories of how floral subsidies affect food webs and why only a minority of cases of natural enemy enhancement translates into reduced crop damage will be critical.

The potential for achieving control of pest damage by manipulating the physical and biological environment of the crop is enormous. However, the potential for causing unintended effects on crop yields is similarly large. Scientific research has investigated the mechanisms by which new and traditional cultural methods of control influence levels of pest populations. This provides an understanding which provides the basis for predicting whether a practice is likely to achieve the desired level of pest control. There is still much to be learned about the complex relationships between the many components of agroecosystems and as our knowledge grows, we will be more and more able to ‘engineer’ agroecosystems to enhance biological control.

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ROLE OF HABITAT MANAGEMENT TECHNOLOGIES IN THE CONTROL OF CEREAL STEM AND COB BORERS IN SUB-SAHARAN AFRICA

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ABSTRACT

Floral and faunal biodiversity is relevant to pest management in many ways. In the present paper emphasis is given to the use of alternative wild and cultivated host plants as trap plants, mixed cropping and management of soil nutrients through mineral nutrition and use of leguminous cover crops in crop rotation systems for integrated control of maize cob and stem

borers in sub-Saharan Africa. Our findings indicate that hydromorphic inland valleys (IVs) are reservoirs for borers and their natural enemies in upland maize fields. Populations of *Busseola fusca* (Fuller) (Lepidoptera: Noctuidae), the most important borer in Cameroon, were low in IV maize fields, increased and reached high levels during the first and second cropping season in adjacent upland maize fields, while egg parasitism of borers was 40 % higher in the dry compared to the first rainy seasons, in IV and upland maize fields, respectively. Thus, IVs should be targeted for inundative releases in biological control programs. Wild host plants, namely grasses, are highly attractive to ovipositing female moths. However, results from laboratory studies on the survival of immature stages of stem borer on different grass species showed that no *Sesamia calamistis* (Hampson) (Lepidoptera: Noctuidae) and *Eldana saccharina* (Walker) (Lepidoptera: Pyralidae) larvae pupated on *Pennisetum polystachion* (L.) Schult, indicating the role of wild hosts as trap plants in the vicinity of maize fields. Depending on the wild host plant and borer species, larval densities were reduced by 30-60 % in maize fields surrounded by wild grasses. Consequently up to twofold higher levels of plant damage were recorded in maize without compared to maize with surrounding grasses. Depending on the crop association and planting pattern, intercropping maize with non-host plants reduced egg and larval densities of borers by 52.6-73.7 % and 34.3-51.5 %, respectively, compared to a maize monocrop. Consequently maize yield losses due to stem borers were up to twofold lower in inter- than in monocrops. All intercropping systems had the additional advantage of higher land productivity than the maize monocrop. A maize-cassava intercrop was most efficient in terms of land use, and thus recommendable for land-constrained poor farmers. Average densities of *B. fusca* at 42 days after planting were generally higher after maize-maize and additional nitrogen (N) fertilization of 60 or 120 kg/ha than after a short fallow of leguminous food or cover crops, and higher after legumes than after maize-maize without additional N doses. However, egg-larval mortalities were up to twofold lower in maize-maize compared to legume-maize treatments. As a result, extent of dead-hearts did not vary significantly among treatments. The average yield losses due to borers were five times higher in the maize-maize sequence without additional N compared to both a legume-maize sequence and maize-maize and additional N dose treatments, suggesting that an increased nutritional status of the plant enhanced both borer fitness and plant vigor, but with a net-benefit for the plants.

INTRODUCTION

Maize, *Zea mays* L., is an important component of the farming systems in sub-Saharan Africa (SSA), where it is a staple for a large proportion of the population. Food security and human nutritional status of small-scale and resource-poor farmers are directly impacted by losses in quantity and quality of the harvested crop. In some cases, losses due to pests and diseases, both pre- and post-harvest, far outweigh any reasonable hope for increases in productivity through improved germplasm and pre-harvest management. The most damaging field pests of maize in SSA are lepidopterous stem and cob borers belonging to the families Noctuidae, Pyralidae and Crambidae (see overview by Polaszek 1998). Stem and cob borers such as *Sesamia calamistis* Hampson, *Busseola fusca* (Fuller) (both Lepidoptera: Noctuidae), *Eldana saccharina*

(Walker), *Mussidia nigrivenella* Ragonot (both Lepidoptera: Pyralidae) are indigenous to Africa and have moved on to maize after having evolved on native grasses or cereals such as sorghum and millet, and other host plant species. In contrast *Chilo partellus* (Swinhoe) (Lepidoptera: Pyralidae) has been accidentally introduced from Asia (Nye 1960). In recent years maize is increasingly replacing indigenous cereal crops, such as sorghum and millet, as well as wild habitats in SSA; consequently it has become the major host of insect pests.

Yield losses in areas with severe borer problems vary between 10-70% (Bosque-Pérez and Mareck 1991; Cardwell *et al.* 1997; Sétamou *et al.* 2000). In addition, grain damage by lepidopterous borers predisposes maize to pre- and post-harvest infestations by storage beetles, infections by *Aspergillus flavus* Link and *Fusarium verticillioides* (Saccardo) Nirenberg, and subsequent contamination with mycotoxins (Cardwell *et al.* 1997; Sétamou *et al.* 2000). Results from diagnostic surveys indicate that the pest situation in SSA is complex, and that the relative importance of a borer species varies between regions (western vs. eastern Africa), eco-regions within a country, or even within the same eco-region of neighboring countries. In West Africa, the most frequently reported maize pests are *S. calamistis*, *E. saccharina* (Bosque-Pérez and Mareck 1990; Gounou *et al.* 1994; Schulthess *et al.* 1997), and the noctuid *S. botanephaga* (Tams and Bowden) (Endrody-Younga 1968). *B. fusca* is generally of low importance in West Africa but the predominant species across all eco-zones in Cameroon (Cardwell *et al.* 1997; Chabi-Olaye *et al.* 2005a,b; Ndemah 1999; Schulthess *et al.* 1997). The crambid *Coniesta ignefusalis* Hampson, a pest of millet in the Sahelian and savanna regions (Nwanze 1991), is occasionally found on maize in all eco-zones. Other species found in the system are *S. poephaga* Tams and Bowden, mainly a minor pest of sorghum in the Guinea and Sudan savannas (Schulthess *et al.* 1997), and *Chilo* spp. (Moyal and Tran 1991). In East and southern Africa, the most damaging cereal borers are *C. partellus*, particularly in warmer lowland areas (Nye 1960), and *B. fusca* (Overholt *et al.* 1994).

Habitat management strategies, in which available natural resources such as wild hosts and non-host plants of stem borers are used against indigenous stem borer species, can increase the understanding of interactions between pests, their cultivated and wild hosts, as well as their natural enemy fauna on both types of host plants (Khan *et al.* 2000; Ndemah *et al.* 2002; van den Berg *et al.* 2001). In general, wild hosts are believed to be a reservoir for stem borers and responsible for pest outbreaks on crops (Bowden 1976; Sampson and Kumar 1986). However, other authors have argued that grasses harbor natural enemies that prevent stem borers from reaching damaging levels on crops or act as trap plants (Schulthess *et al.* 1997). Recent studies by Chabi-Olaye (unpublished data) indicated that hydromorphic inland valleys (IVs), in which maize is grown during the dry season, maintain carry-over populations of not only *B. fusca* but also of its natural enemies in the humid forest of Cameroon. These findings show that a more complete understanding of the role of wild hosts and IVs in insect pest outbreaks will be useful in generating suitable management strategies for lepidopterous cob and stem borers.

In many regions of SSA maize is traditionally intercropped with various other crops. Generally intercropping allows more efficient land use, and ensures the availability of food throughout the seasons (Mutsaers *et al.* 1993; Vandermeer 1989). The importance of plant biodiversity in agro-ecosystems for reducing crop losses by pests has long been recognized (Baliddawa 1985; Litsinger and Moody 1976; Okigbo and Greenland 1976). A considerable

number of studies have shown that pest populations are higher, more frequent and cause greater yield losses in monocrops than in more diverse cropping systems (Altieri and Letourneau 1982; Cromartie 1981; Kareiva 1983; Risch *et al.* 1983). Such a habitat management strategy has also been tested against stem borers in SSA. A considerable reduction in stem borer densities was found when maize was intercropped with non-hosts such as cassava or legumes (overview by van den Berg *et al.* 1998). Mixed cropping systems also have additional advantages such as a higher land productivity and are thus recommendable for land-constrained poor farmers who do not use external inputs such as fertilizer.

It is known that favorable nutrition often improves the ability of plants to withstand pest attack (Chabi-Olaye *et al.* 2005a; Denké 1995; Sétamou *et al.* 1993; 1995). Moreover, surveys by Ndemah (1999) showed a negative relationship between *B. fusca* densities and potassium (K) content of soil, suggesting that improvements of soil fertility can complement pest control measures in Africa.

The present paper reports on the development of habitat management technologies against cob and stem borers in SSA, and discusses the implications for their adoption by small-scale farmers in SSA.

MATERIALS AND METHODS

ROLE OF CULTIVATED INLAND VALLEYS

During the dry season in the humid forest zone of Cameroon, maize is the most important cash crop grown in hydromorphic inland valleys (IVs). Such dry season fields, however, may also be reservoirs for pests such as *B. fusca* and its natural enemies, which invade adjacent upland maize fields during the rainy seasons. From 2002 through 2004 we monitored pest and parasitoids in IVs and nearby upland maize fields. Surveys in each year started during the dry season in the IVs and were extended to upland maize fields during the first and second cropping seasons. Depending on the availability of maize, 10-12 IV maize fields were investigated per dry season. During the first and second cropping season, 1-2 up-land maize fields were sampled around each cultivated IV. Fields were visited two times, i.e., at the vegetative stage and at harvest. At each visit, 24 maize plants were sampled destructively. Data on the number of borer eggs, parasitized eggs, larval densities and their parasitism were gathered.

WILD HOST SURVEY

The wild grasses *Sorghum arundinaceum* (Desv.) Stapf, *Panicum maximum* Jacq., *Andropogon gayanus* Kunth, *Pennisetum polystachion* (L.) Schult and *P. purpureum* Moench are known to be the most common alternative host plants of stem borers in SSA (Khan *et al.* 1997; 2000; Gounou and Schulthess 2004; Schulthess *et al.* 1997; van den Berg *et al.* 1997), and their abundance is strongly negatively related to borer incidence in maize fields (Cardwell *et al.* 1997; Schulthess *et al.* 1997). Differences in the relative abundance of borers and the survival of their progeny in the different wild host species may provide some clues for the management of stem borers. The data presented here are based on results of surveys carried out in Benin, Ghana, and Cote d'Ivoire (Gounou *et al.* 2004; Schulthess *et al.* 1997). Sampling was carried out through the first and second growing season along roadside fields at 10-25 km intervals.

Additional samples were also taken in IVs. At each sampling site 100-200 grass tillers were randomly sampled. The number of infested tillers was counted, and plants were dissected and borers collected, and counted according to species level. In addition, *S. calamistis* and *E. saccharina* were reared on pieces of stems from the before mentioned five grass species and larval survival was recorded (Shanower *et al.* 1993).

USE OF ALTERNATIVE WILD AND CULTIVATED HOST PLANTS AS POTENTIAL TRAP PLANTS

Wild hosts, i.e., *S. arundinaceum*, *P. maximum*, and *P. polystachion* in Benin and *P. purpureum* in Cameroon, were evaluated as trap plants for stem borers in field experiments. Experiments were carried out during the first and second growing season of 1997 in the humid forest zone of Cameroon, and in the second growing season of 1999 in the derived savanna zone of Benin. 100-144 m² maize plots were surrounded by 1 m border rows of grasses. Grass tufts were planted during the first season of 1997 in Cameroon, and the second season of 1998 in Benin. A control treatment of non-surrounded maize was planted away from the maize-grass treatments to reduce interactions between treatments. Each treatment was replicated four times. Maize was planted at 53,333 plants/ha. Two to three weeks after planting maize plants received NPK fertilizer (15:15:15) at a rate of 160-250 kg in Benin and Cameroon, respectively. Fields were kept weed free. 21 days after planting (DAP), 24 maize plants were randomly sampled at two-weekly intervals for assessment of plant damage (% stems bored and % dead-hearts), borer abundance and their natural enemies. Five to eight samplings were taken in Benin and Cameroon, respectively.

M. nigrivenella has been frequently reported as a pest of maize (Bosque-Pérez and Mareck 1990; Gounou *et al.* 1994; Moyal 1988; Moyal and Tran 1991) and cotton, *Gossypium hirsutum* L. (Silvie 1990; Staebli 1977). High infestations of *M. nigrivenella* were also reported from velvetbean *Mucuna pruriens* DC. and jackbean *Canavalia ensiformis* (L.) DC. (Schulthess and Gounou unpublished data). The two leguminous cover plants are green manure crops, introduced to Africa in the last decades for improving soil fertility and controlling weeds (Carsky *et al.* 1998; Vissoh *et al.* 1998;) and are increasingly used by farmers in SSA. A detailed study on the infestation and preference of *M. nigrivenella* on maize, cotton, jack- and velvetbeans was carried out by Sétamou (1999). The experimental design consisted of a randomized block with three replications containing four plots of 25 m x 25 m each. The distance between blocks was 4 m, and that between plots within a block 2 m. Each host plant was planted in early May 1995 at a density of 31,250 and 25,000 plant stands/ha for maize and cotton, respectively, and 16,500 plants/ha for both jack- and velvetbeans. Maize and cotton crops received NPK (15-15-15) fertilizer at a rate of 200 kg/ha, two weeks after sowing. For each crop, sampling started as soon as 50 % of the fruits were formed. The borer populations were monitored at weekly intervals until harvest. The percentage of fruits infested with all stages of *M. nigrivenella* in the sample was calculated for each host plant on each sampling date.

INTERCROPPING

In these experiments, conducted in the humid forest zone of Cameroon, four crop species were used, i.e., a 110-day open pollinated variety of maize (Cameroon Maize Series [CMS]

8704), a late maturing soybean *Glycine max* (L.) Merr. (var. TGX 1838-5E), an erect type of cowpea *Vigna unguiculata* (L.) Walp. (var. Asonten) and a local variety of cassava *Manihot esculenta* Crantz (called 'automatic' by farmers). Maize was grown as a monocrop or intercropped with cassava, cowpea or soybean. In the intercropping treatments, maize was planted 12-14 days after the non-host plants. Two spatial arrangements were used in the intercrops, i.e., (i) a within row arrangement where each maize plant was followed by a non-host plant, and (ii) strip planting in which two rows of maize were followed by two rows of a non-maize crop, with one row of non-host plants as first and last row borders. Each experiment had a control plot with an insecticide treatment to allow an estimation of yield losses due to borer attack. Insecticides were applied to maize 21 and 42 DAP, using carbofuran at ca. 1.5 a.i. kg ha⁻¹ by placing the granules in the whorl. The treatments were arranged in a completely randomized block design with four replications. Plots were 6 × 12 m each. The planting patterns were chosen such that maize populations in all intercrops were the same (26,667 plants/ha) except in the case of alternate hill planting with cassava where the plant population was reduced to 20,000 plants/ha. In the monocrops plant densities were chosen to be 'optimal' for the region, i.e., those that produce the highest yield.

During the vegetative stage, 80 and 40 maize plants/plot were checked weekly in the mono- and intercrops, respectively, for stem borer egg batches. Larval densities were evaluated on 24 and 12 randomly sampled plants per plot in mono- and intercrops, respectively. Sampling started 28-35 DAP and was continued at biweekly intervals until maturity of maize cobs. At each sampling date, maize plants were dissected and borer larvae and pupae were identified to species and counted on a per plant/plot level. Borer tunnel length and maize yields were estimated on four pre-determined sub-plots of 1.5 m x 2 m per treatment at harvest.

IMPROVED PLANT NUTRITION THROUGH MINERAL FERTILIZER AND LEGUMINOUS COVER CROPS

In 2003, field trials were set up in the humid forest zone of Cameroon to assess the effect of maize-legume cropping sequences and continuous maize growing with and without mineral fertilizer on both stem borer infestations, with a special emphasis on *B. fusca*, and maize yield losses. In the long-short rainy seasons sequence (herewith referred to experiment 1), cover crops were planted mid March and left to grow from March to August of the same year, thus covering the long rainy season. The succeeding maize crop was sown on September 5 of the same year. In the short-long rainy seasons sequence (herewith referred to experiment 2), which lasts from September to August in the next year, cover crops were planted on September 15 and the succeeding maize on March 25. The maize-maize cropping system had three levels of mineral fertilizer, i.e., 0, 60 and 120 kg N/ha. Each experiment had a control plot with an insecticide treatment to allow an estimation of yield losses due to borer attack. The treatments were arranged in a completely randomized block design with four replications. Plots were 6 x 6 m each. The cover crops were cut about four to five weeks before planting of the succeeding maize crop, and their biomass retained on the plots without incorporation into the soil. N was applied in form of urea. The two different N-levels (60 and 120 kg/ha) were equally split in two and three dosages, respectively, and were applied 14, 28 and 56 DAP. All maize planting was done at a spacing of 75 cm between rows and 50 cm within rows. Four

seeds of 110-days open pollinated maize (cv. Cameroon Maize Series (CMS) 8704) were sown per hill, and the stands were thinned to two plants per hill 14 DAP. Plots were manually kept weed free. Insecticides were applied to maize 21 and 42 DAP, using carbofuran at ca. 1.5 a.i. kg ha⁻¹ by placing the granules in the whorl. Twelve plants per plot were sampled destructively every two weeks starting from 21 DAP until harvest. The number of borer eggs and larvae per plant and percentage of plants with dead-heart symptoms were recorded in insecticide-free plots. For each treatment, borer tunnel length and maize yield were estimated on four pre-determined sub-plots of 1.5 m x 2 m at harvest.

STATISTICAL ANALYSES

Differences in plant infestation, pest abundance and damage variables, i.e., % stems bored, dead-hearts and yield losses were analyzed by analysis of variance (ANOVA), using the general linear model (GLM) procedure of SAS (SAS 1997). The t-test with Bonferroni probability adjustment was used to compare the different wild host plants and seasons. The variation in pest abundance in the mixed cropping systems over sampling days was analyzed by ANOVA, using the mixed model procedure of SAS with repeated measures (SAS 1997). Least squares means (LSM) were separated using the t-test. The significance level was set at $P = 0.05$. The effect of host plants on *M. nigrivenella* infestation levels was evaluated using the closed testing procedures (Hochberg and Tamhane 1987). The percentage of fruits infested for each host plant species were ranked within sampling date. The Chi-square test was then applied on the total sum of ranks of each host plant, to evaluate independence of *M. nigrivenella* infestations according to host plants using the PROC FREQ procedure of SAS (SAS 1997). Maize yield losses due to cob and stem borers were assessed on an area basis as follows:

$$100 \times (Y_i - Y_t) / Y_i$$

where Y_i and Y_t are the mean yields of insecticide-treated and non-treated plots, respectively.

The overall efficiency of intercropping systems was assessed using the land-equivalent-ratio (LER). It is calculated after Mead and Willey (1980) as follows:

$$LER = (I_a / M_a) + (I_b / M_b)$$

where I_a and I_b are the yields of crops a and b, respectively, in intercropping; M_a and M_b are the yields of crops a and b, respectively, in the monocrops. If the LER is > 1 , the intercrop is more efficient in terms of land use and if it is < 1 the monoculture is more efficient.

RESULTS

ROLE OF INLAND VALLEYS

The percentage of plants infested and larval densities varied significantly between IV and upland maize fields (Table 1). Percentage plants infested and borers densities did not differ between the first and second growing seasons, and the averages were 3.3 and 5.0 times, respectively, lower than in the dry season/ IV (Table 1). *B. fusca* was the most abundant borer

species across seasons and no differences were found in its abundance among seasons (Table 1). However, *Sesamia* sp. and *M. nigrivenella* densities were 14.6 and 3.1 times, respectively, higher in the dry season/ IV than in the first and second growing seasons (Table 1). Few borer larvae and pupae were parasitized. However, levels of egg parasitism were similarly high during the dry/ IV and the second growing seasons, and the average being 1.7 times higher than during the first growing season.

Table 1. Infestation, abundance and parasitism of stem borers in inland valley and up-land maize fields in the humid forest zone of Cameroon.

Variables	Cropping seasons ¹		
	Dry	First	Second
Infested plants (%)	15.0 ± 2.2b	45.6 ± 5.3a	53.3 ± 9.5a
No. of larvae/plant	0.55 ± 0.04b	2.85 ± 0.63a	2.63 ± 0.80a
Species abundance (%)			
<i>B. fusca</i>	70.5 ± 4.2a	90.4 ± 3.0a	89.7 ± 5.4a
<i>Sesamia</i> sp.	18.2 ± 5.5a	1.5 ± 0.5b	1.0 ± 0.3b
<i>E. saccharina</i>	8.3 ± 1.2a	7.2 ± 2.4a	8.3 ± 4.6a
<i>M. nigrivenella</i>	2.9 ± 0.4a	0.9 ± 0.3b	1.0 ± 0.6b
Parasitism (%)			
Egg	43.2 ± 6.0a	26.1 ± 1.0b	43.9 ± 1.6a
Larvae + pupae	3.5 ± 1.8a	4.2 ± 2.0a	5.2 ± 2.3a

¹The first and second growing seasons last typically from mid March to mid July and from mid August to end of November, respectively. The major dry season starts in the third week of November and lasts through end of February or beginning of March of the following year. Within row means followed by the same letters are not significantly different at $P = 0.05$ (Bonferroni t-test).

ROLE OF WILD AND CULTIVATED LEGUMINOUS HOST PLANTS

Borer densities did not significantly differ among the most often reported wild hosts (Table 2). However, the percentage of infested tillers was significantly higher in *S. arundinaceum* compared to the other plants (Table 2). *S. calamistis* was most abundant on *P. maximum* and *P. polystachion* and less on *P. purpureum* (Table 2). By contrast, *B. fusca* was more frequently found on *P. purpureum* than on *S. arundinaceum* and no *B. fusca* larvae were collected on other plants. However, percentage of larvae-pupal survival was < 7 % on all five wild hosts and on *P. polystachion* no *S. calamistis* and *E. saccharina* and on *P. maximum* no *E. saccharina* larvae pupated (Table 2).

Both in the derived savanna of Benin and humid forest of Cameroon, borer densities were significantly reduced in maize surrounded by wild gramineous hosts compared to non-surrounded maize (Table 3). *S. calamistis* and *E. saccharina* densities were reduced by 51.2 % and 34.1 %, respectively, in maize surrounded by wild hosts compared to the non-surrounded one in the derived savanna of Benin. However, *E. saccharina* densities did not differ among surrounded and non-surrounded maize in both the derived savanna of Benin and the humid forest zone of Cameroon. However, in Cameroon, *B. fusca* density was 1.7 times lower in

maize surrounded by *P. purpureum* compared to non-surrounded maize (Table 3). Consequently, depending on the grasses the percentage of stems bored was 1.2-2 times in Benin and 2.2 times in Cameroon lower in maize plots surrounded by grasses than in the non-surrounded maize (Table 3). In the derived savanna of Benin the percentage of egg parasitism was 2.0-2.3 times higher in surrounded compared to non-surrounded maize (Table 3).

Table 2. Relative abundance of stem borers, their incidence and survival of progeny on wild host plants investigated in West Africa.

Variables	Wild host species				
	<i>Andropogon gyanus</i>	<i>Panicum maximum</i>	<i>Pennisetum purpureum</i>	<i>Pennisetum polystachion</i>	<i>Sorghum arundinaceum</i>
Infested tillers (%)	4.9 ± 0.7b	11.0 ± 3.6b	7.1 ± 2.0b	3.2 ± 0.6b	25.2 ± 4.6a
No. of borers/plant	0.23 ± 0.2a	0.46 ± 0.3a	0.91 ± 0.7a	0.29 ± 0.2a	1.15 ± 0.5a
Abundance (%) ¹					
<i>S. calamistis</i>	66.1 ± 2.7b	90.8 ± 2.1a	12.5 ± 5.8c	78.8 ± 3.0ab	74.9 ± 4.8ab
<i>E. saccharina</i>	33.9 ± 2.7a	9.2 ± 2.1b	10.7 ± 4.4b	21.2 ± 4.0ab	17.7 ± 4.2b
<i>B. fusca</i>	0b	0b	76.9 ± 7.5a	0b	7.4 ± 1.5b
Survival (%) ²					
<i>S. calamistis</i>	0.3	0.3	1.0	0	6.5
<i>E. saccharina</i>	0.3	0	0.3	0	3.5

¹Relative abundance of borer species calculated as percentage of density of the species over total borers collected;

²Data from Shanower *et al.* (1993). Within rows, means followed by the same letters are not significantly different at P = 0.05 (Bonferroni t-test).

Table 3. Least square means of stem borer numbers and plants damaged in maize surrounded and not surrounded by different grass species in Benin: *Pennisetum polystachion* (Ps), *Sorghum arundinaceum* (Sa) and *Panicum maximum* (Pm); and in Cameroon: *P. purpureum* (Pp).

Variables ¹	Derived Savanna, Benin				Humid Forest, Cameroon	
	Maize only	Maize with Pm	Maize with Sa	Maize with Pm	Maize only	Maize with Pp
<i>S. calamistis</i> ²	0.86a	0.41bc	0.51b	0.34c	-	-
<i>E. saccharina</i>	0.31a	0.27a	0.27a	0.27a	0.06a	0.09a
<i>B. fusca</i>	-	-	-	-	0.50a	0.30b
% stem bored	11.2a	9.5ab	8.1b	5c	7.9a	3.6b
% dead-heart	18.3a	18.1a	9.5c	15.6b	-	-
% egg parasitism	42.6b	85.0ab	95.0a	98.8a	-	-

¹Data from Ndemah *et al.* (2002).

²In number of borers per plant. Within rows, means followed by the same letter per country are not significantly different at P = 0.05 (t-test).

There were significant differences between the sums of fruit infestation ranks (Table 4) of the different host plants ($\chi^2 = 65.33$, $df = 6$, $P < 0.001$). Infestation of *M. pruriens* pods was significantly higher than that of maize and cotton ($\chi^2 = 13.0$, $df = 4$, $P < 0.05$), but there were no significant differences among the sums of the infestation ranks of maize and cotton when tested alone ($\chi^2 = 5.6$, $df = 3$, $P > 0.05$). *C. enseiformis* had significantly higher number of pods infested compared to *M. pruriens* ($\chi^2 = 24.0$, $df = 3$, $P < 0.001$). Hence, the closed testing procedure revealed that *M. nigrivenella* infestation was significantly highest on *C. enseiformis*, with highest levels at all sampling occasions (Table 4).

Table 4. Sum of weekly ranks of *Mussidia nigrivenella* infestation levels observed on four crops in Benin.

Cultivated Crops ¹	Sum of Infestation Rank			
	1	2	3	4
<i>Zea mays</i> L	0	0	5	7
<i>Gossypium hirsutum</i> L.	0	4	5	3
<i>Mucuna pruriens</i> DC	0	8	2	2
<i>Canavalia enseiformis</i> (L.) DC.	12	0	0	0

¹Data from Sétamou (1999).

INTERCROPPING

Results of the analysis of variances showed that egg batch and larval densities of *B. fusca* were not affected by the crops associated with maize in the intercropping treatments (Table 5). However, the egg batch density differed significantly between strip and within row planting (Table 5). Thus, the egg batch and larval densities, as well as the damage variables were presented per spatial arrangement.

Intercrops of maize with non-host plants significantly reduced the oviposition, infestation and damage due to borers compared to maize monocrop (Table 6). Yet, overall the within row planting reduced the borer egg batches per plant by 73.7 % and larval abundance by 51.5 % compared to sole maize, but treatments did not differ in terms of egg-larval mortality (Table 6). The percentages of stems bored and yield losses did not differ between the two spatial arrangements of the intercrops, and were 5.2 and 2.0 times lower than in the maize monocrop for strip and within row planting, respectively (Table 6).

Table 5. Results of ANOVA on the differences in borer densities between treatments (data pooled across sampling days and seasons).

Source of variance ¹	Egg batch/plant			<i>Busseola fusca</i> /plant		
	d.f.	F	P-value	d.f.	F	P-value
Spatial arrangement (SA)	1; 177	23.57	< 0.001	1; 88	0.85	0.368
Crop (C)	2; 177	1.38	0.253	2; 88	0.19	0.830
SA*C	2; 177	1.59	0.207	2; 88	0.04	0.961

¹Two spatial arrangement, i.e., strip and within row planting. The non-host plants cropped with maize are cassava, cowpea and soybean

The overall efficiency of intercrops is presented in Figure 1. The greater land-equivalent-ratios were obtained when maize was associated with cassava (LER ranged between 1.6 and 1.8). The lowest LER was recorded in maize-legumes with values ranging between 1.15 and 1.45 (Fig. 1).

Table 6. Effect of intercropping on the oviposition, infestation and damage (least square means \pm SE) due to *Busseola fusca* in the humid forest of Cameroon.

Spatial Arrangement	Oviposition and infestation			Damage	
	Egg Batch per Plant	<i>B. fusca</i> per Plant	Mortality ¹ (%)	% Stem Bored	% Yield Loss
Maize monocrop	0.38 0.04a	1.34 \pm 0.22a	97.1 \pm 0.6a	28.4 \pm 2.1a	34.2 \pm 5.8a
Maize + non-host plant strip-planted	0.18 \pm 0.02b	0.88 \pm 0.13b	97.4 \pm 0.6a	6.5 \pm 1.2b	16.9 \pm 3.3b
Maize + non-host plant within-row planted	0.10 \pm 0.02c	0.65 \pm 0.12b	96.8 \pm 1.1a	4.5 \pm 1.2b	16.8 \pm 3.3b

¹Egg to larva mortality; within columns, means followed by the same letter are not significantly different at P = 0.05 (t-test).

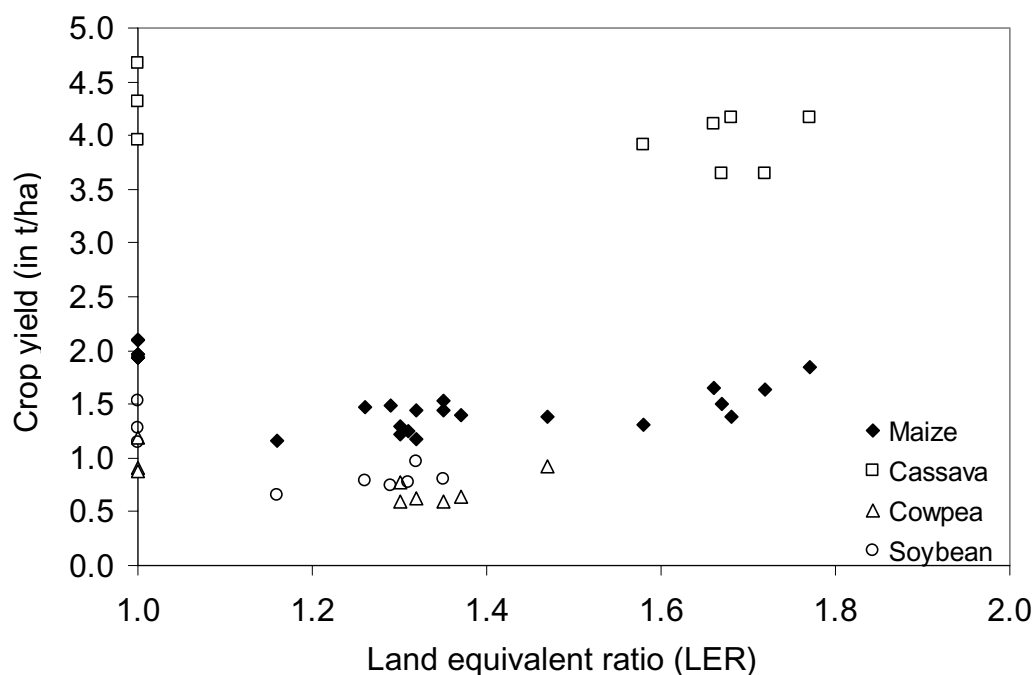


Figure 1. Relationship between land equivalent ratio and crops (maize and associated crops in the intercrops) yields.

PLANT NUTRITION

For both experiments, differences in *B. fusca* larval densities were significant at 42 DAP, while no differences were found among treatments at 63 DAP (Table 7). Average densities of *B. fusca* at 42 DAP and egg-larval mortalities were generally higher following maize-maize with 60 or 120 kg N/ha than following legumes, and higher after both leguminous plants than after maize-maize without additional N (Table 7). Data on stem tunneling and yield losses differed significantly among treatments while no such differences were found in both experiments in the percentages of dead-hearts (Table 7).

In both experiments the greatest extent of stem tunneling was found in the maize-maize and 120 kg N/ha treatment, and no difference was found between the maize after legumes and the maize-maize without additional N treatments (Table 7). By contrast, in both experiments the highest yield losses were found in the maize-maize without additional N treatment. Overall, *B. fusca* densities at 42 DAP and the extent of stems tunneled were 1.1-1.4 and 1-1.8 times, respectively, higher in experiment 1, where maize was planted during the long-short rainy seasons sequence, than in experiment 2, where maize was planted during the short-long rainy seasons sequence.

Table 7. Effect of different fallow and rotation systems on least square means (\pm SE) of *Busseola fusca*, egg to larvae mortality and damage variables in the humid forest of Cameroon.

Treatments ¹	<i>B. fusca</i> per plant		Egg-larva mortality (%)	Stem tunneling (cm)	Dead-hearts (%)	Yield loss (%)
	42 DAP	63 DAP				
Experiment 1						
Maize-maize	1.67 \pm 0.3c	1.22 \pm 0.1a	45.9 \pm 2.5c	22.0 \pm 4.8b	3.8 \pm 0.3a	25.0 \pm 1.1a
Maize-maize + 60 kg ha ⁻¹	4.25 \pm 0.5a	1.11 \pm 0.2a	88.2 \pm 4.8a	24.7 \pm 4.9b	4.1 \pm 0.3a	6.1 \pm 1.0b
Maize-maize + 120 kg ha ⁻¹	4.58 \pm 0.3a	1.19 \pm 0.1a	91.5 \pm 5.1a	59.8 \pm 4.7a	4.0 \pm 0.3a	3.7 \pm 1.1b
Maize-soybean	2.62 \pm 0.3b	1.13 \pm 0.1a	70.3 \pm 3.2b	14.8 \pm 4.1b	3.7 \pm 0.2a	4.9 \pm 0.9b
Maize-mucuna	3.33 \pm 0.2b	1.10 \pm 0.1a	69.2 \pm 3.8b	16.9 \pm 4.2b	4.1 \pm 0.2a	4.6 \pm 1.0b
Experiment 2						
Maize-maize	1.39 \pm 0.2d	1.03 \pm 0.2a	38.4 \pm 3.1c	19.5 \pm 1.9b	2.8 \pm 0.3a	17.4 \pm 1.0a
Maize-maize + 60 kg ha ⁻¹	3.03 \pm 0.1ab	1.33 \pm 0.2a	85.8 \pm 3.5a	20.4 \pm 2.0b	2.9 \pm 0.4a	2.6 \pm 1.1b
Maize-maize + 120 kg ha ⁻¹	3.22 \pm 0.2a	1.41 \pm 0.1a	88.2 \pm 4.2a	32.0 \pm 1.8a	3.0 \pm 0.3a	1.8 \pm 1.0b
Maize-soybean	2.46 \pm 0.1bc	1.21 \pm 0.1a	63.3 \pm 3.4b	15.7 \pm 1.6b	3.2 \pm 0.2a	4.1 \pm 0.9b
Maize-mucuna	2.67 \pm 0.2c	1.19 \pm 0.1a	58.5 \pm 2.8b	16.2 \pm 1.8b	3.6 \pm 0.2a	3.2 \pm 0.9b

¹Experiment 1 was conducted during the long and short rainy seasons sequence and Experiment 2 during the short and long rainy seasons sequence. Within columns, means followed by the same letter are not significantly different at P = 0.05 (t-test).

DISCUSSION

Results of the countrywide surveys on stem and cob borers in West Africa so far showed that borers oviposited heavily on wild host plants but their relative importance, both on maize and wild grasses, varied between regions, eco-zones and within the same eco-zone (Schulthess *et al.* 1997). *S. calamistis* and *E. saccharina*, the most frequently reported maize borers in West Africa (Bosque-Pérez and Mareck 1990; Gounou *et al.* 1994; Schulthess *et al.* 1997), were found in several grasses, but *S. calamistis* was seven times more abundant on *P. maximum* and *P. polystachion* than on *P. purpureum*, while *E. saccharina* was equally abundant on the three surveyed grasses. However, depending on the grass species *S. calamistis* abundance was 1.5-10 times higher than that of *E. saccharina*. *B. fusca*, the predominant borer in the humid forest of Cameroon (Chabi-Olaye *et al.* 2005b; Ndemah 1999; Schulthess *et al.* 1997), where wild grasses are scarce (Ndemah *et al.* 1999), was 10.3 times higher on *P. purpureum* than on *S. arundinaceum*. Given the geographic distribution of stem borers and the role of wild host plants, Schulthess *et al.* (1997) argued that the differences in relative importance of species may be due to differences in human population densities. Increasing population pressure and the concomitant expansion of agricultural areas often result in deforestation and displacement of wild habitats of borers, which probably affect the population dynamics of both borers and their natural enemies.

In the humid forest of Cameroon, lower densities of *B. fusca* were found in the IVs compared to up-land maize fields during the first and second cropping seasons. However, its abundance compared to other borer species in the area did not vary considerably among seasons. By contrast, *S. calamistis* density was > 90 % higher in IVs than in up-land maize fields. Chabi-Olaye *et al.* (2001), using eggs of *B. fusca* and three *Sesamia* spp. as hosts, showed that all four hosts yielded similar levels of parasitism by the sceliotid *Telenomus isis* (Polaszek), egg emergence and sex ratios. In the present study, egg parasitism was up to twofold higher in IVs than in the upland maize fields. These findings suggest that IVs planted with maize during the dry season maintain carry-over populations of not only *B. fusca*, but also of its natural enemies, as well as of alternative minor hosts such as *S. calamistis*. Thus, if crops grow concurrently in IVs and upland fields in an area, the chances of emerging borer females to encounter a suitable host plant, e.g., maize, for oviposition and survival of their progenies, and ensuing overall pest densities in an area increase. IVs therefore should be targeted for inundative releases of egg parasitoids against *B. fusca* with the aim of reducing yield losses in adjacent up-land maize fields.

Results from different field trials in Benin and Cameroon where grasses were grown as border rows around maize plots lead to reduced borer densities in such maize fields compared to non-surrounded maize stands (Ndemah *et al.* 2002). Oviposition and development studies with *S. calamistis* and *E. saccharina* carried out in Benin, using a range of grass species, showed that borers oviposited heavily on grasses (Sekloka 1996; Semeglo 1997; Shanower *et al.* 1993), but larval mortality was nearly 100 % (Shanower *et al.* 1993). Thus, these grasses acted as trap plants and hence can provide natural control for stem and cob borers. Promising grass species in SSA are among others sudan grass *Sorghum vulgare* var. *sudanense* Hitchc., a commercial fodder grass, molasses grass *Melinis minutiflora* Beauv., a non-host forage plant, and silverleaf desmodium *Desmodium uncinatum* (Jacq.) DC (Khan *et al.* 1997; 2000). In

West and Central Africa the most reported grass species are *P. purpureum* and *P. maximum* (Innes 1977; Ndemah et al. 2002; Schulthess et al. 1997).

Recent work in western Africa showed, that maize intercropped with cassava or grain legumes considerably reduced maize yield losses due to *S. calamistis* (Schulthess et al. 2004) and *B. fusca* (Chabi-Olaye et al. 2005b), as a result of reduced oviposition of adult moths. The value of such cropping systems has been extensively reviewed by Baliddawa (1985) and van Emden and Dabrowski (1994). Overall, these authors concluded that intercropping contributes to the diversity of agro-ecosystems and can reduce population build-up of insect pests. However, not all attempts to control pests through mixed cropping have been successful. Especially the choice of the associated crops and the spatial arrangements for the intercrops is of outmost importance. In our study higher reduction in *B. fusca* oviposition was observed in within row planting compared to strip planting, though both arrangements did not differ in terms of their land-equivalent ratios. Combined maize-cassava crops yielded a higher land-equivalent ratio than maize-legumes. In addition, a study by Sétamou (1999) showed that *M. nigrivenella* preferred jack- and velvetbeans than maize. Thus, with the increasingly popular practice of using cover crops in maize production systems in SSA to improve soil fertility, *M. nigrivenella* populations could greatly increase on these plants, thereby endangering the following maize crop. However, clever timing can produce the opposite effect, i.e., if the emergence of the maize tassels coincides with pods formation on the legumes, as then the attractive pods will cause *M. nigrivenella* to oviposit principally on jack- and velvetbeans (Sétamou 1999).

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In our experiments in the humid forest of Cameroon, the leguminous fallow systems and the maize-maize and additional N treatments had significantly higher stem borer densities. However, the borer-induced grain yield losses were considerably lower than in the continuous maize cultivation without additional N fertilization. These results confirm previous findings by Sétamou et al. (1995) who hypothesized that an increased nutritional status of the plants enhance both borer fitness and plant vigor, but with a net benefit for the plants. Thus, improving soil fertility can effectively complement pest control.

Results from the presented studies provide an increased understanding of the role of IVs on the population dynamics of maize cob and stem borers in SSA. Moreover, if properly managed, increased crop-plant diversity can considerably reduce the build-up of pest populations and increase the yield of maize, thus becoming an interesting land-use strategy for resource-poor and land-constrained farmers in SSA.

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THE POTENTIAL ROLE OF INSECT SUPPRESSION IN INCREASING THE ADOPTION OF COVER CROPS

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ABSTRACT

We used a survey of attendees of an organic farming conference in Minnesota, U.S.A., to determine whether farmers would be more likely to adopt a fall-seeded winter rye cover crop preceding soybeans if doing so could aid in the suppression of soybean aphid, *Aphis glycines* Matsumura (Homoptera: Aphididae). Of the 24 soybean growers that responded to our survey, 22 indicated that they would be more likely to either adopt or retain this cover cropping practice if it could aid in soybean aphid suppression. Insect pest suppression may therefore be an effective way to augment adoption of cover cropping practices.

INTRODUCTION

Fall-seeded winter cover crops have the potential to improve soil organic matter, reduce soil erosion, manage excess nutrient loads, and provide for weed and insect management. While the benefits of cover crops to soil fertility, nutrient scavenging, and erosion and weed control are well-documented, research showing improvement in insect control has lagged behind in many cover-cropping systems. To illustrate this, we did a literature search on the AGRICOLA database to compare the number of scientific citations associated with cover crops and terms associated with 'soil', 'weeds' and 'insects'. There was a clear deficit of citations associated with the term 'insects' and 'insect control' when paired with 'cover crop' (Table 1).

Table 1. Number of references recovered by AGRICOLA searches for the period 1984-2004 when 'cover crops' (CC) was entered along with one other term.

Terms Entered	Number of References
CC and soil	803
CC and soil fertility	181
CC and organic matter	125
CC and weeds	159
CC and weed control	253
CC and insects	26
CC and insect control	41

Indeed, judging by this brief search, it would appear that only two scientific articles per year have been published on the effects of cover crops on insect control, compared with more than 12 per year on the effects of cover crops on weed control.

Despite all of the documented benefits of cover crops, they have seen relatively low adoption rates in midwestern corn/soybean production areas in the U.S. (DeBruin *et al.* 2005; Stoskopf 1985). Reasons for low adoption include perceived logistic difficulties in the establishment of fall-planted cover crops and apprehension that yields may suffer in cover-cropped systems. We hypothesize that the adoption rate of cover crops would be increased by a clear demonstration that their use could result in improved insect pest control.

THE RYE SYSTEM

We are testing the effect of a fall-seeded winter rye (*Secale cereale* L.) cover crop following corn and preceding soybeans to aid in the suppression of the soybean aphid, *Aphis glycines* Matsumura (Homoptera: Aphididae). Rye is a well-adapted fall-seeded cover crop for the northern U.S.A., exhibiting exceptional winter hardiness as well as the ability to emerge and grow at low temperatures under a wide soil moisture and soil fertility range. Rye seeds are drilled into corn residue to produce an overwintering rye stand that resumes growth in spring (Porter 2004). Soybeans are drilled into the rye stand at approximately the same time as soybeans are typically planted by organic producers in the Upper Midwestern U.S. (late May – early June). At this point, the rye can be up to three feet in height. The rye is mowed using a flail mower or stalk chopper when soybeans can be up to 6 inches tall (V1, V2 stage).

A number of lines of reasoning suggest that fall-seeded rye cover crops would reduce soybean aphid pressure in soybeans. First, work in numerous cropping systems other than soybeans has demonstrated reduced densities of pest aphids in the presence of various forms of increased vegetational diversity (reviewed by Gurr *et al.* 2000). Second, studies in China have shown that soybeans intercropped with corn at a very small spatial scale have lower densities of soybean aphids than monoculture soybeans (Wu *et al.* 2004). And lastly, some

organic soybean growers in Minnesota experimenting with fall-seeded rye cover crops have reported reduced soybean aphid densities and increased densities of soybean aphid predators in cover-cropped fields (Porter 2004). Winter rye could aid in soybean aphid suppression either by reducing colonization of soybean by soybean aphid in the early season and/or by enhancing natural enemies (predators, parasitoids and pathogens) of soybean aphid (Pickett and Bugg 1998). We have preliminary data showing that winter rye harbors aphid natural enemies including aphid parasitoids, coccinellid beetles, and syrphid flies, in the spring during the time that soybean aphid colonization typically occurs (Table 2).

Table 2. Aphids and aphid natural enemies collected from overwintered rye at the University of Minnesota Agricultural Experiment Station, St. Paul, Minnesota, in 2004.

Date	Aphid Species	Natural Enemy
5/26/2004	<i>Rhopalosiphum padi</i> <i>Sitobium avenae</i> <i>Schizahis graminum</i>	<i>Coccinella septempunctata</i> <i>Harmonia axyridis</i> <i>Aphidius</i> sp. (reared from <i>S. graminum</i>)
6/4/2004	<i>R. padi</i> <i>S. avenae</i> Unidentified aphid sp.	<i>C. septempunctata</i> <i>C. trifasciata</i> <i>H. axyridis</i> <i>Coleomegilla maculata</i> <i>Aphelinus</i> sp. (adult) Unidentified Syrphidae

Coccinellid beetles are the most important predators of soybean aphid in the midwestern U.S. (Fox *et al.* 2004; Rutledge *et al.* 2004), as well as in China (Liu *et al.* 2004; Wu *et al.* 2004). At one of our field sites, the native *Coleomegilla maculata* is present in soybean fields early in the season (i.e., when grain aphids would be present on winter rye), and the exotic *Harmonia axyridis* is present later in the season (Fig. 1). Entomopathogenic fungi are also present in soybean fields, but they tend to become active in July or August, which is after the winter rye is mowed in our system (Fig. 2). It remains to be seen whether the altered microclimate associated with winter rye will encourage earlier epizootics of entomopathogenic fungi in soybean aphid populations.

THE SURVEY

We used a one-page written survey of attendees of the 2005 Minnesota Organic and Grazing Conference and Trade Show, held in St. Cloud, MN, on Jan. 21 – 25, 2005, to evaluate the hypothesis that soybean growers would be more likely to utilize fall-seeded winter rye as a cover crop preceding soybean if this practice could aid in soybean aphid suppression. We were particularly interested in the opinions of organic growers because they cannot use conventional insecticides to control the soybean aphid. To our knowledge, no organically-approved sprays have been shown to be effective against the soybean aphid. The survey was aimed at soybean growers, and we asked respondents whether they farmed organically or conventionally, whether they had ever had problems with soybean aphid, and whether they

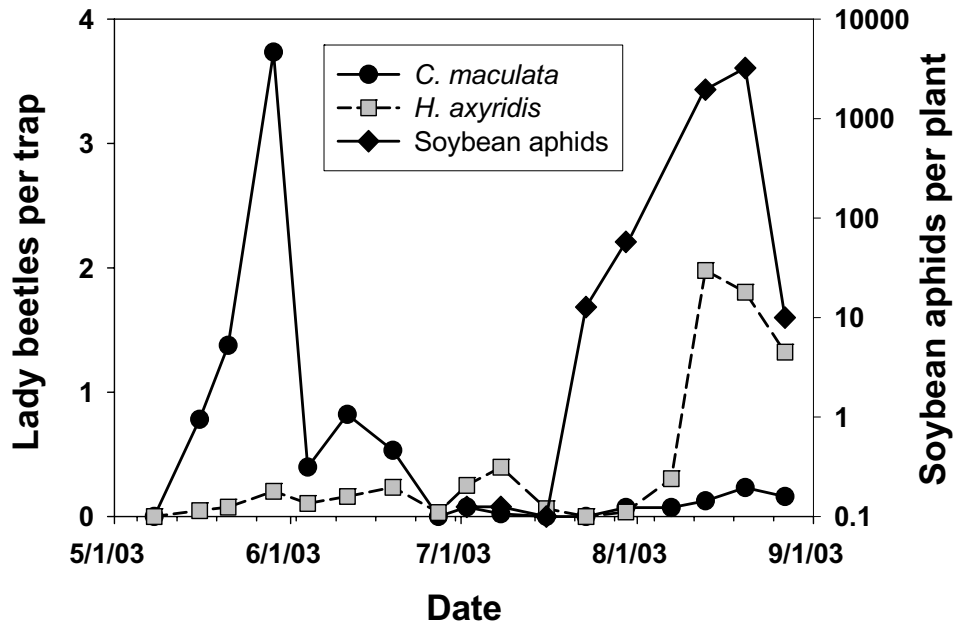


Figure 1. Average numbers of two species of lady beetles (*Coleomegilla maculata* and *Harmonia axyridis*) and soybean aphids (log scale) in soybean fields in 2003 in Lamberton, MN, U.S.A.

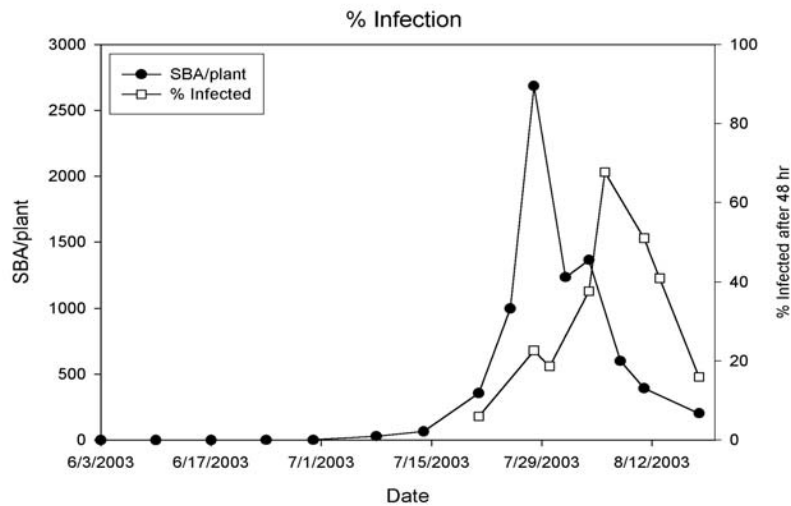


Figure 2. Soybean aphid population, 2003 and prevalence of entomopathogenic fungi in a 48h bioassay of field collected aphids, Rosemount, MN.

had ever used a fall-seeded rye cover crop preceding soybeans. For those growers that had problems with soybean aphids, we asked what management tactics they used (if any) to suppress them, and for those growers that reported having planted a winter rye cover crop, we asked for the primary reason for the use of this tactic. Finally, we asked whether respondents would be more likely to either use the fall-seeded rye cover crops for the first time, or continue using them, if they could aid in the suppression of soybean aphid. The surveys were passed out at a luncheon during the conference and at a symposium presentation on insect pests. The conference had 277 registered attendees, and we received 25 completed surveys. The results of the survey are presented in Table 3.

Table 3. Summary of grower survey results^a: rye cover crops and soybean aphid (SBA) management.

Questions	Organic growers	Conventional growers	Growers using both practices
Q1) Have you had problems with SBA?			
A) Yes	9	1	2
A) No	9	3	0
Q2) If so, what management tactic was used for SBA?			
A) None	3	0	0
A) Organic insecticide	4	0	1
A) Non-organic insecticide	0	1	0
Q3) Do you use fall-planted rye cover crops?			
A) Yes	13	1	1
A) No	5	3	1
Q4) If so, why do you use the rye cover crops?			
A) Weed management	9	0	0
A) Soil management	2	0	0
A) Weed and soil management	2	1	1
Q5) If not already using rye cover crops, would you be more likely to do so if it could aid in suppressing SBA?			
A) Yes	4	1	1
A) No	0	1	0
Q6) If already using rye cover crops, would you be more likely to continue doing so, if it could aid in suppressing SBA?			
A.) Yes	12	1	1
A.) No	1	0	0

^aOf the 25 growers who responded, 24 grew soybeans (18 organic growers, 4 conventional growers, and 2 growers using both practices).

Out of the 24 respondents that grew soybeans, 18 used exclusively organic methods, four were conventional growers, and two used both organic and conventional practices. Overall, one-half of the respondents reported having had problems with soybean aphid, and of the organic growers with soybean aphid problems, about half did nothing to manage them, and half used organically-approved insecticides. Overall, more than 60% of the soybean growers (15/24) reported using fall-planted rye cover crops. We believe this to be an overestimate of the state-wide adoption of rye winter cover crops. We suspect that growers that use cover crops are more likely to attend the organic farming conference and/or more likely to respond to a survey with the term ‘cover crop’ in the title. It appears from our results that organic farmers are more likely to use the rye cover crop than conventional growers are (72% vs. 25%), but the number of respondents (especially conventional growers) is too small to

assess this question properly. The main reason cited for the use of winter rye was weed management, but soil management issues (organic matter augmentation, erosion control) were cited as well.

Our survey showed very clearly that adoption of winter rye cover-crops would likely increase if this practice could aid in the suppression of soybean aphid. Of seven respondents that had never used winter rye, six indicated that they would be more likely to use rye if it could aid in the suppression of soybean aphid. Similarly, of 15 respondents that had already been using rye cover crops, 14 indicated that they would be more likely to continue using rye if it could aid in the suppression of soybean aphid.

Thus, cover crop-associated insect suppression (either via reduced pest colonization and/or improved biological control) is a potential means to increase adoption of cover cropping practices, which themselves produce benefits that are felt beyond the farmers' fields, such as nutrient scavenging and reduced soil erosion.

ACKNOWLEDGEMENTS

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USING SYNTHETIC HERBIVOR-INDUCED PLANT VOLATILES TO ENHANCE CONSERVATION BIOLOGICAL CONTROL: FIELD EXPERIMENTS IN HOPS AND GRAPES

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ABSTRACT

The potential of using synthetic herbivore-induced plant volatiles (HIPV) as a cultural tool to enhance conservation biological control of insects and mites is being researched in hops and grapes in Washington State. Results to date indicate that a number of natural enemy species in the families, Chrysopidae, Hemerobiidae, Anthocoridae, Geocoridae, Miridae, Coccinellidae, Syrphidae, Braconidae, Empididae and Mymaridae, are attracted to sticky traps baited with aqueous methyl salicylate (MeSA), hexenyl acetate, farnesene or octyl aldehyde. Hop yards and grape blocks baited with controlled release sachet (CRS) dispensers of MeSA recruit larger populations of some insect predators (e.g., *Stethorus punctum picipes* Casey (Coleoptera: Coccinellidae), *Orius tristicolor* White (Hemiptera: Anthocoridae), *Chrysopa nigricornis* Burmeister (Neuroptera: Chrysopidae) than unbaited blocks, resulting in some instances, in improved biological control of spider mites and aphids. CRS dispensers of methyl salicylate, methyl jasmonate and hexenyl acetate increased populations of two parasitic wasp genera (*Anagrus*, *Metaphycus*) in grapes, possibly by 'signalling' to the plants to produce HIPVs. The use of synthetic HIPVs/plant-signalling compounds as 'Herbivore-Induced Plant Protection Odors' (HIPPOs) has the potential to provide a novel yet practical strategy for improving the efficacy and reliability of conservation biological control in a variety of agricultural ecosystems.

INTRODUCTION

The use of conservation biological control (CBC) as a component of integrated pest management in agriculture is a strategy that is increasing in importance and popularity (Barbosa 1998). Concurrent with the increasing use of CBC in agriculture has been a realization that 'generalist' natural enemies (i.e., those that have a broad prey preference) can often play a major role in pest suppression (Symondson *et al.* 2002). Thus CBC as a strategy that enhances guilds or communities of both specialist and generalist natural enemies is now viewed as a pest management strategy, very likely to improve crop protection. Another factor that has encouraged and enhanced the use of CBC in many crop systems is the availability and use of

pesticides that are narrow-spectrum and safe to many beneficial insects and mites (James 2002; 2003d; 2004).

CBC research in many crop systems is focused on improving reliability by strengthening the natural enemy community both in terms of population density and species diversity (Cardinale *et al.* 2003). Inevitably there are two aspects of this problem that need to be addressed; 1) attraction of beneficial arthropods to the crop during early cropping phases and 2) maintenance of these populations throughout the life of the crop. Kean *et al.* (2003) identified 'spatial attraction' of natural enemies as the best way of enhancing CBC. Their results suggested an almost linear relationship between natural enemy attraction and prey equilibrium. The use of semiochemical attractants (e.g., host/prey-derived chemicals) to increase recruitment and retention of beneficial arthropods in crop ecosystems, is an area of opportunity for enhancement of CBC.

Herbivore-Induced Plant Volatiles (HIPV) offer the best potential for developing effective and practical semiochemical-based strategies for manipulating natural enemy populations. Plants attacked by herbivores emit specific chemical signals. These are the 'words' of a complex language used to 'warn' other plants of impending attack and to recruit predatory/parasitic arthropods for 'bodyguard' services. Such plant 'bodyguards' respond to plants in distress, and benefit from the food/host resources available (Sabelis *et al.* 1999). A voluminous body of literature now exists on this phenomenon, first demonstrated in a series of elegant laboratory investigations based on a bean plant-spider mite-predatory mite system (Sabelis and Dicke 1985; Sabelis and Van de Baan 1983; Sabelis *et al.* 1984). The qualitative and quantitative characteristics of HIPV can vary according to the herbivore involved, the plant species and even genotype (Takabayashi *et al.* 1994; Turlings *et al.* 1993). HIPV may function as direct attractants and/or as plant signals. Airborne or topically applied methyl jasmonate (MeJA) can act as a plant signal by causing the emission of volatiles in some plants mimicking those produced in response to herbivore damage (Hunter 2002). There is some evidence that methyl salicylate and hexenyl acetate may also function as plant signals (Engelberth *et al.* 2004; Ozawa *et al.* 2000; Shulaev *et al.* 1997). The use of HIPV as signalers or elicitors of 'correct' and complete blends of natural enemy attracting emissions, is an attractive possibility for manipulating predator and parasitoid populations in pest management.

Compared with the abundance of laboratory studies on HIPV, there is a dearth of field-based studies (Hunter 2002). The first demonstration of the impact of HIPV in the field came from research on biocontrol of psyllids in pear orchards in the Netherlands (Drukker *et al.* 1995), which showed that densities of predatory bugs (Anthocoridae) increased with the density of caged psyllids. Shimoda *et al.* (1997) recorded more predatory thrips on sticky cards near spider mite-infested bean plants than on traps near uninfested plants. Bernasconi *et al.* (2001) trapped more natural enemies near plants damaged and treated with caterpillar regurgitant, than near undamaged, untreated plants.

The first direct evidence for the potential of synthetic HIPV as field attractants for beneficial insects came from this research group (James 2003a,b,c) which demonstrated attraction of a number of insect species and families to methyl salicylate (MeSA) and (Z)-3-hexenyl acetate (HA) in Washington hop yards. Insects attracted to MeSA included *Chrysopa nigricornis* Burmeister (Chrysopidae), *Geocoris pallens* Stal. (Geocoridae), *Stethorus punctum picipes*

(Casey) (Coccinellidae) and species of Syrphidae. Three species were attracted to HA, a predatory mirid, *Deraeocoris brevis* (Uhler), an anthocorid, *Orius tristicolor* (White) and *S. punctum picipes*. Subsequent synthetic HIPV/trapping studies revealed at least 13 species or families of beneficial insects responded to one or more synthetic HIPV (James 2005). Thirteen HIPV attracted one or more species/family of beneficial insect.

Evidence for recruitment and retention of beneficial insects in grapes and hops using controlled-release (CR) dispensers of MeSA, was presented by James and Price (2004). In a replicated experiment conducted in a juice grape vineyard, sticky cards in blocks baited with MeSA captured significantly greater numbers of five species of predatory insects (*C. nigricornis*, *Hemerobius* sp., *D. brevis*, *S. punctum picipes*, *O. tristicolor*) than unbaited blocks. Four insect families (Syrphidae, Braconidae, Empididae, Sarcophagidae) were also significantly more abundant in the MeSA-baited blocks, as indicated by sticky card captures. Monitoring conducted in a MeSA-baited hop yard indicated development and maintenance of a beneficial arthropod population that was nearly four times greater than that in an unbaited reference yard. The large population of predatory insects in the MeSA-baited hop yard was associated with a dramatic reduction in spider mite and aphid numbers, and sub-economic populations were maintained for the rest of the season. The evidence presented in James and Price (2004) is highly suggestive that the use of controlled-release MeSA in a crop could increase recruitment and residency of populations of beneficial insects. Here, we report additional data from field experiments in 2004 on the use of synthetic HIPVs to enhance CBC.

MATERIALS AND METHODS

RECRUITMENT OF BENEFICIAL INSECTS TO HOP YARDS AND VINEYARDS

CR dispensers containing MeSA (5 g, 98%, Chem-Tica International, Costa Rica) were deployed in four hop yards and three vineyards (one juice grape, two wine grape) in south-central Washington State during May-September 2004. A control yard with similar characteristics (size, variety etc) was also established, 1-2 km from each MeSA site. Dispensers were stapled to supporting posts (~ 0.5 m above ground) in the yards. Dispenser deployment density for the vineyards was A – 336, B – 432 and C – 642, and for the hop yards, A – 180, B – 447, C – 516 and D – 556 per hectare. Beneficial and pest arthropod populations were monitored weekly at each site (including controls) by examining leaf samples, conducting canopy shake sampling and by retrieving/replacing four yellow sticky cards stapled to poles (see James and Price 2004) for full sampling methodology). Insecticide and miticide applications were kept to a minimum at all sites and where possible, chemicals known to have minimal effect on beneficial arthropods were used. Sticky cards were positioned randomly within each hop yard or vineyard and separated by at least 10 m. After collection, they were examined in the laboratory and all beneficial insects identified and counted. Trap data were analyzed using either the Mann-Whitney Rank –Sum Test, or the Kruskal-Wallis ANOVA on ranks.

ATTRACTION OF PARASITIC WASPS TO HIPV-BAITED GRAPES

A field experiment was conducted in an unsprayed 10 ha juice grape (cv. Concord) vineyard in south central Washington State during May-September 2004, to determine the attraction of synthetic formulations of three HIPV, MeSA, methyl jasmonate (MeJA) and (Z)-3-hexenyl acetate (HA) to parasitic wasps. CR dispensers containing 5 g (MeSA), or 1 g (HA, MeJA) were prepared and supplied by Chem-Tica Internacional (Costa Rica). The dispensers for each HIPV were deployed in three 8 X 30 m blocks distributed in a completely randomized design with three unbaited blocks in the vineyard. Each block contained 65 grapevines (5 rows of 13 vines) and blocks were separated by a minimum of 100-m. In the HIPV blocks, 14 dispensers were deployed on April 29 with half stapled at the base of supporting posts and the remainder attached to trellis wires at approximately 1.5 m above the ground. Both deployment types were evenly and alternately distributed in each block giving an approximate density equivalent to 586/ha. Dispensers were replaced on July 15. Populations of parasitic wasp species were monitored using three yellow sticky cards per block, equally spaced (8 m apart) along the center row. Cards were collected and replaced weekly. Parasitic wasps (Mymaridae, Encyrtidae) were identified to genus (*Anagrus* and *Metaphycus*) and counted in the laboratory under a stereomicroscope. At two weekly intervals small samples (~25 individuals) of trapped *Anagrus* spp. were identified to species using a compound microscope and the key of Triapitsyn (1998). Trapping data were analyzed using either the Kruskal-Wallis ANOVA on ranks (KW), with means separated by Dunn's method, or the Mann-Whitney Rank-Sum Test (MW).

RESULTS

RECRUITMENT OF BENEFICIAL INSECTS TO HOP YARDS AND VINEYARDS

Hop yards. All of the unbaited control yards were treated with at least one miticide (for twospotted spider mite, *Tetranychus urticae* Koch) and/or insecticide (for hop aphid, *Phorodon humuli* Schrank). The control yard for site B was treated with abamectin and imidacloprid, pesticides known to be harmful to some beneficial insects (James 2001; James and Voge 2001), thus this pair was not used in this analysis. The remaining control yards were treated with bifenthrin and/or pymetrozine, both of which are considered safe to most beneficial arthropods in hops (James 2002). MeSA sites A and D were not treated with any insecticide/miticide, while site C received one application of the aphicide, pymetrozine and another of *Bacillus thuringiensis*. The MeSA-baited hop yards developed larger populations (3-5 X) of predatory insects than corresponding unbaited yards (Figs. 1-2). Predatory insect species that were significantly more abundant in MeSA-baited yards than unbaited yards included *O. tristicolor*, *G. pallens*, *D. brevis* and *Stethorus* spp (Fig. 2). Other species and families recorded and quantified but pooled here as 'predatory insects' included lacewings (Chrysopidae, Hemerobiidae), hover flies (Syrphidae), aphidophagous lady beetles (Coccinellidae), predatory thrips (Thripidae) and damsel bugs (Nabidae). Numbers of the predatory hemipterans, *O. tristicolor*, *G. pallens* and *D. brevis* were combined and were six times more abundant in the high deployment rate MeSA yards than in the corresponding control yards (Fig. 2). The

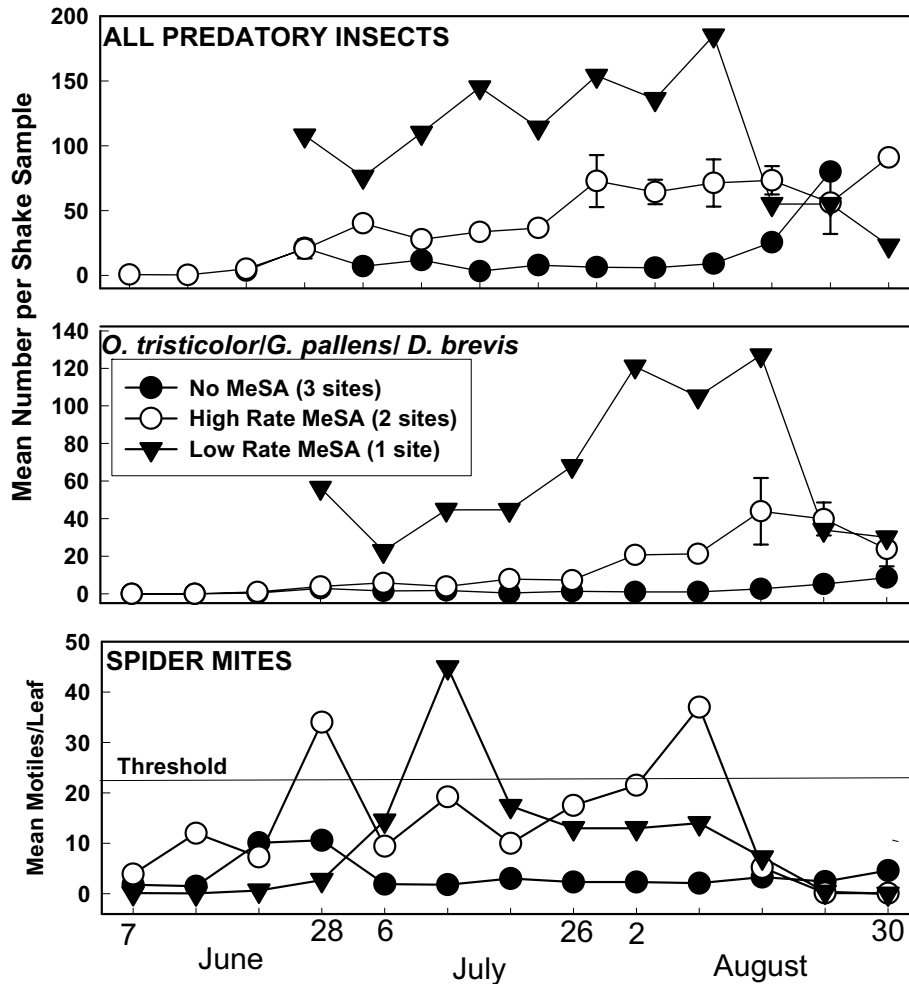


Figure 1. Mean (\pm SE) abundance and phenology of predatory insects and spider mites in hop yards baited with low (180 dispensers/ha) and high (516/556 dispensers/ha) deployment rates of MeSA or left unbaited.

difference was even greater between the low deployment rate yard and corresponding control yard (21.5 X). Similarly, mite-eating lady beetles (*Stethorus* spp.) were 23.5 X more abundant in the low rate MeSA yard than in the control yard (sticky card data) (Fig. 2). Predatory insect abundance was greater and earlier in establishment in the low rate yard than in the high rate yards (Fig. 1). Spider mite populations in the MeSA-baited yards, briefly exceeded the recommended miticide spray threshold (Fig. 1).

In the low rate MeSA yard spider mites exceeded 40 motiles/leaf for a week in early July but stayed below the threshold for the rest of the season. Similarly, populations in the high rate yards briefly climbed above 30 motiles/leaf in late June and again in mid-August. However, hop cone yield and quality were not affected in the MeSA yard and were comparable to those obtained in the non-MeSA yards. Large populations of predatory insects remained in the MeSA-baited yards during August despite the relatively low numbers of spider mites and aphids (e.g., in the low rate MeSA yard there was a mean of 4.9 ± 2.1 mites/aphids per leaf/week in August). Other arthropod prey (e.g., thrips) were also present and may have helped sustain the generalist predator community.

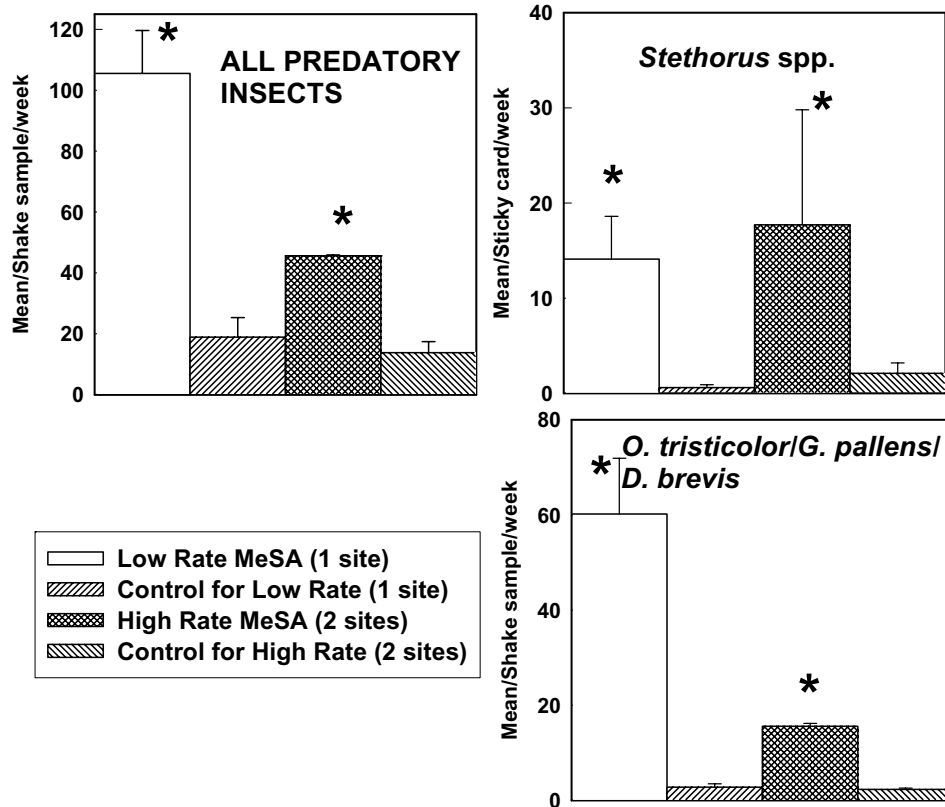


Figure 2. Mean (\pm SE) abundance of predatory insects (all taxa combined), *Stethorus* spp., *O. tristicolor*, *G. pallens* and *D. brevis* in MeSA-baited and unbaited hop yards during May-September 2004. Columns marked with asterisks are significantly greater than the corresponding control column ($P < 0.05$).

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Vineyards. Predatory insect populations in vineyards were much smaller than in hop yards. However, significant differences in the abundance of some species or families (e.g., Chrysopidae, *D. brevis*, *Stethorus* spp.) between MeSA-baited and unbaited sites were indicated by sticky card captures (Fig. 3).

ATTRACTION OF PARASITIC WASPS TO HIPV-BAITED GRAPES

Only two genera of Hymenoptera occurred commonly; *Anagrus* spp. (Hymenoptera: Mymaridae) and *Metaphycus* sp. (Hymenoptera: Encyrtidae). *Metaphycus* sp. appeared to be a parasitoid of scale insects, primarily *Parthenolecanium corni* (Bouche), present on vines in the vineyard. *Anagrus* spp. trapped in this study represented at least three species (*A. erythroneuræ* Triapitsyn and Chiappini, *A. daanei* Triapitsyn, *A. tretiakovæ* Triapitsyn), all important in biological control of grape leafhoppers in Washington State (Storm 2002). Leafhopper and scale insect populations appeared to be evenly distributed throughout the vineyard. Analyses conducted for the entire sampling period showed that significantly greater numbers of *Metaphycus* sp. were trapped in MeSA, MeJA and HA-baited blocks than in unbaited blocks (Fig. 4) ($P < 0.001$, $H = 63.68$, $df = 3$, KW). Greater numbers were trapped in MeJA and HA-baited blocks than in MeSA-baited blocks ($P < 0.001$, $T = 3531$ (MeJA), $T =$

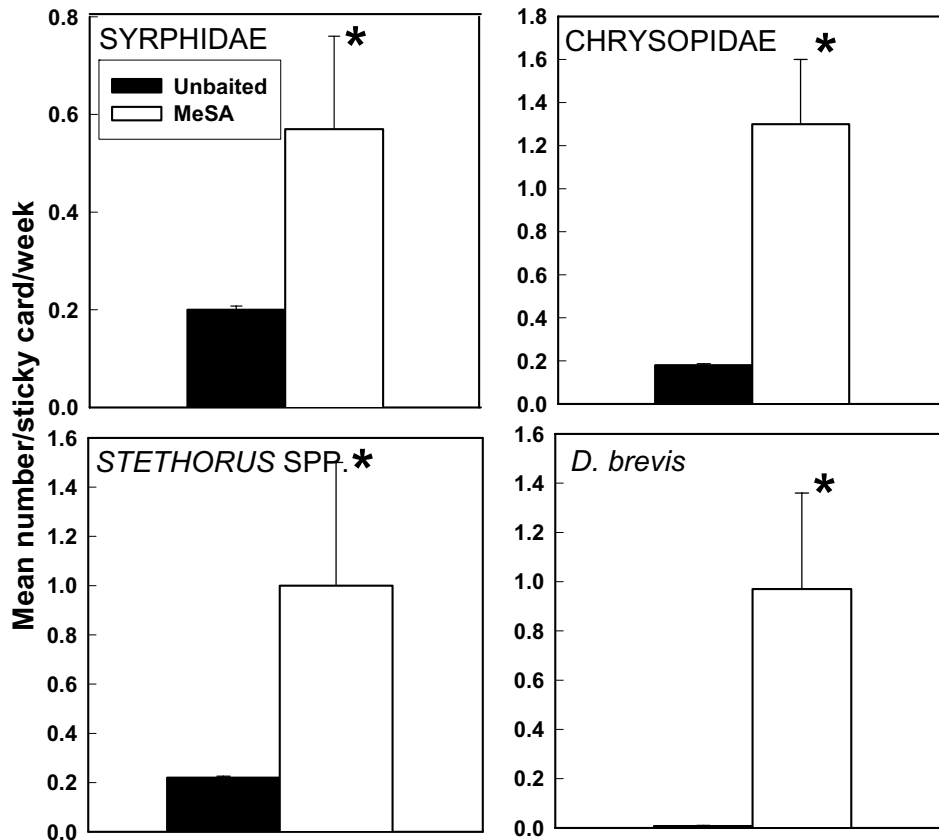


Figure 3. Mean (\pm SE) abundance of Syrphidae, Chrysopidae, *Stethorus* spp. and *D. brevis* in MeSA-baited and unbaited vineyards during May-September 2004 as indicated by sticky card captures. Columns marked by an asterisk significantly different from corresponding unmarked column ($P < 0.05$).

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3449 (HA), MW), with no difference between MeJA and HA-baited blocks ($P = 0.33$, $T = 3819$, MW).

Greater numbers of *Metaphycus* sp. were trapped in MeJA and HA than in unbaited blocks in all months (May $P < 0.001$, $H = 21.30$, $df = 3$; June $P < 0.005$, $H = 12.99$, $df = 3$; August $P = 0.001$, $H = 53.82$, $df = 3$; September $P = 0.001$, $H = 32.41$, $df = 3$, KW) except July when wasp abundance was low ($P = 0.47$, $H = 2.55$, $df = 3$, KW) (Fig. 5). Numbers of *Metaphycus* sp. trapped in MeSA blocks were significantly greater than in unbaited blocks during August and September only (Fig. 5).

Numbers of *Anagrus* spp. trapped were not significantly different between baited and unbaited blocks when analyzed over the whole trapping period (Fig. 4) ($P = 0.22$, $H = 4.39$, $df = 3$, KW). However, when analyzed on a monthly basis, significantly greater numbers of *Anagrus* spp. were trapped in MeSA-baited and MeJA-baited blocks than in unbaited blocks during August-September (August $P = 0.05$, $H = 10.68$ September $P = 0.001$, $H = 35.38$ $df = 3$, KW) (Fig. 6). Traps in HA-baited blocks caught more *Anagrus* spp. than unbaited blocks during September only ($P < 0.001$, $T = 176$, MW) (Fig. 6).

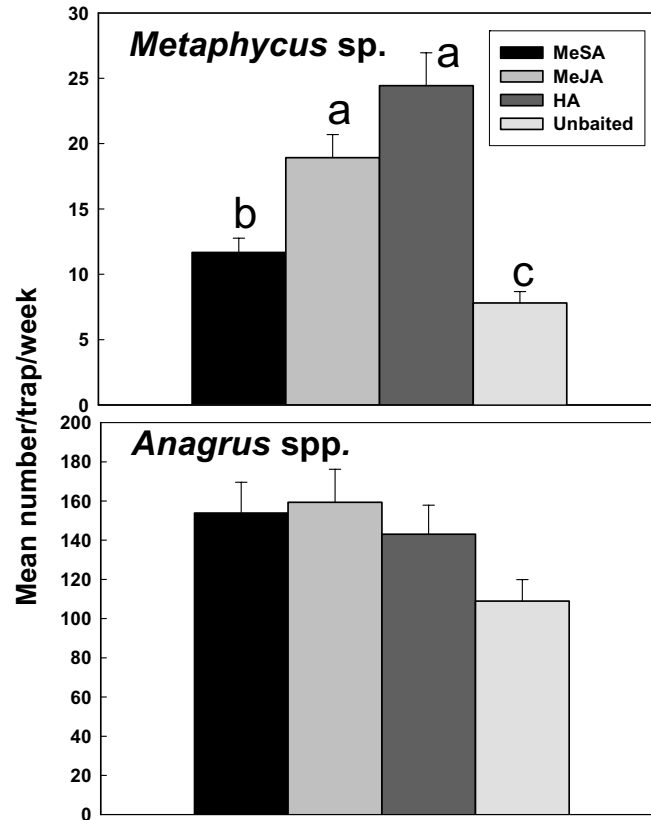


Figure 4. Mean (\pm SE) abundance of *Metaphycus sp.* and *Anagrus spp.* on sticky cards in methyl salicylate (MeSA), methyl jasmonate (MeJA), (Z) – 3 – hexenyl acetate (HA)-baited or unbaited grape blocks during May-September 2004. Different letters on columns denote significant differences for *Metaphycus sp.* ($P < 0.001$). No significant differences for *Anagrus spp.* ($P = 0.22$).

DISCUSSION

The potential of CR dispensers of MeSA for enhancing the recruitment and retention of predatory insects in crops (James and Price 2004), is further supported by the field data presented here. In addition, the attraction of parasitic wasps (not attracted to MeSA, MeJA or HA-baited sticky cards) to blocks of grapevines containing CR dispensers of MeSA, MeJA and HA, raises the possibility that these synthetic HIPV may also have practical application for signaling plants to produce their own HIPV.

Hop yards and vineyards baited with CR dispensers of MeSA at deployment rates of 180-642/hectare harbored larger populations of predatory insects than nearby and comparable yards without dispensers, as indicated by canopy shake sample, sticky card and leaf sample data. The data presented here are only a portion of the total data sets collected for each yard, but are typical of the results obtained. Species that appeared to respond most strongly to MeSA included *Stethorus spp.*, *O. tristicolor*, *G. pallens*, and *D. brevis*. During August up to 200 *Stethorus spp.* per sticky card/week were recorded from MeSA-baited hop yards, and 100-150 predatory bugs (*O. tristicolor*, *D. brevis*, *G. pallens*, Nabidae) could be shaken from each hop plant sampled. The largest populations of predators occurred in the hop yard baited with the lowest number of MeSA dispensers (180/ha), suggesting that the higher deployment rates used (447-642) may have been sub-optimal. It is possible that the atmospheric concen-

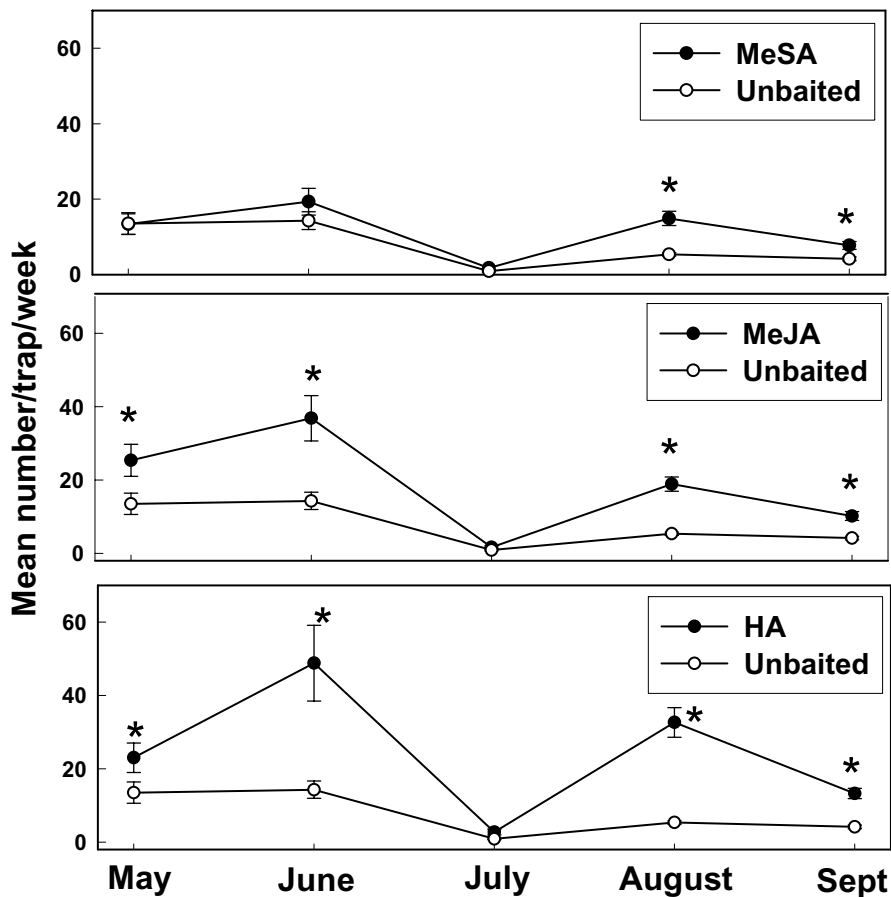


Figure 5. Monthly mean (\pm SE) abundance of *Metaphycus* sp. on sticky cards in methyl salicylate (MeSA), methyl jasmonate (MeJA), (Z) - 3 - hexenyl acetate-baited or unbaited grape blocks during May-September 2004. Asterisks denote significant differences from unbaited blocks ($P < 0.05$).

tration of MeSA in these yards, particularly during spring and early summer, was too high for optimal predator attraction. Predator populations in these yards during July, although higher than in non-MeSA yards, were not as high as in the low deployment rate yard. None of the MeSA-baited hop yards were treated with a miticide and despite short-lived increases in mite populations above the spray threshold, acceptable commercial outcomes in terms of hop cone yield and quality were achieved. The best result was achieved in the low deployment rate yard where mite numbers remained below the spray threshold for all of the cone maturation period (late July-September). The slightly larger populations of spider mites permitted to develop in the MeSA-baited yards (compared to the miticide-treated unbaited yards) may have aided predator recruitment during the summer by direct (numerical aggregation) or indirect means (natural production of HIPV). However, early season spider mite populations in baited and unbaited yards were similar, but the size of predator populations was already differing by late June. The majority of predatory insect species/families attracted to MeSA-baited hops and grapes were generalist feeders. This community of predators will develop and maintain populations even if target prey (e.g., mites), are not abundant as long as alternative prey are available. Another possible advantage of not attracting specialist predators is avoiding selection against responding to synthetic MeSA if nutritional rewards are inadequate.

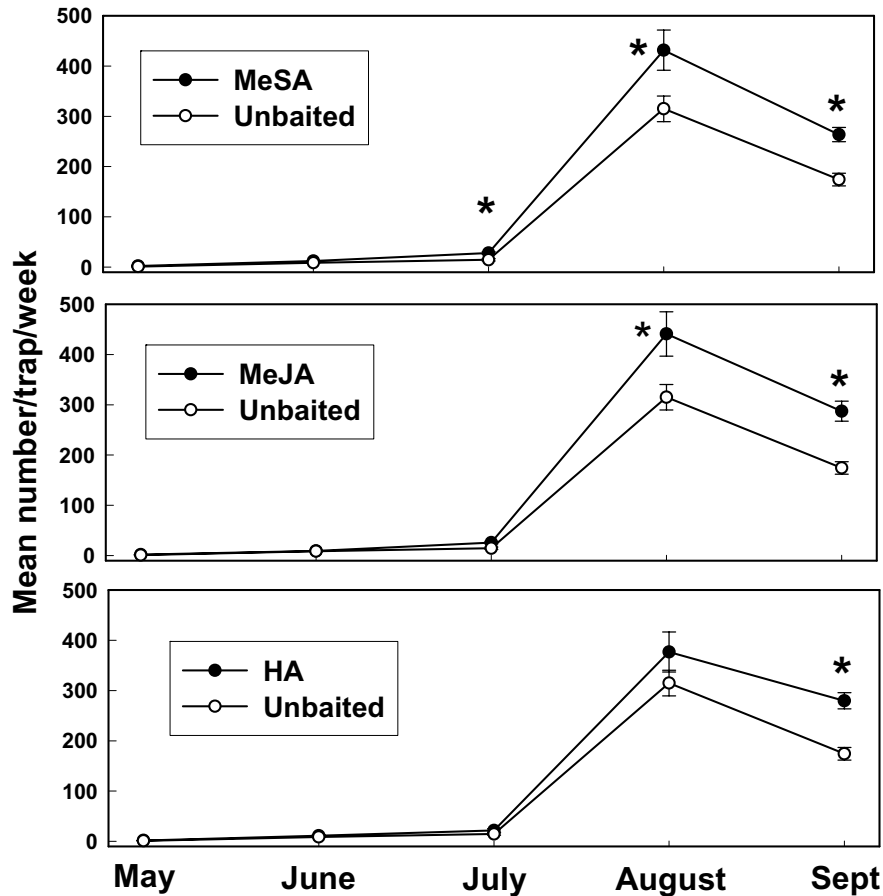


Figure 6. Monthly mean (\pm SE) abundance of *Anagrus* spp. on sticky cards in methyl salicylate (MeSA), methyl jasmonate (MeJA), (Z) – 3 – hexenyl acetate-baited or unbaited grape blocks during May-September 2004. Asterisks denote significant differences from unbaited blocks ($P < 0.05$).

This study also provided evidence for attraction of two genera of specialist parasitic wasps to grapevines baited with MeSA, MeJA or HA. James (2005) reported micro-Hymenoptera (primarily the families Scelionidae, Encyrtidae, Mymaridae (excluding *Anagrus* spp.)) were attracted to MeSA, indole and *cis*- 3- hexen – 1 – ol –baited traps. However, *Angarus* spp. and *Metaphycus* sp. were not attracted to MeSA, MeJA or HA-baited traps in James (2005) or James (2003 b). In the current study, blocks of grapevines baited with controlled-release dispensers of MeSA, MeJA or HA, recruited significantly larger populations of *Metaphycus* sp. and *Anagrus* spp. than unbaited blocks, as judged by their incidence on sticky yellow cards. The effect was strongest for *Metaphycus* sp. with significant responses to the three compounds in all months that these wasps were common. MeJA and HA were more attractive than MeSA. The response by *Anagrus* spp. to baited blocks was confined to late summer and early autumn and greatest responses were seen in the MeSA and MeJA-baited blocks. Numbers of trapped *Anagrus* spp. were small during May-July (means of 1-20 individuals/trap/week) and may have obscured any differences during this period. There was also a shift in species abundance during the season with *A. erythroneuræ* and *A. tretiakovæ* dominating during May-July (65%) and *A. daanei* dominating during August-September (70%).

Anagrus spp. and *Metaphycus* sp. do not respond to sticky traps baited with MeSA, MeJA or HA (James 2003; 2005), although *A. daanei* was attracted to traps baited with *cis*-3-hexen-1-ol, farnesene or octyl aldehyde (James, 2005). James and Price (2004) using controlled-release dispensers of MeSA in the same vineyard used here, noted no difference in *Anagrus* spp. abundance between baited and unbaited blocks. However, almost twice as many MeSA dispensers were used in each block. There is laboratory evidence for a repellent effect of high rates of MeSA on predatory mites (De Boer and Dicke 2004) and it is possible that *Anagrus* spp. were repelled or at least inhibited in the James and Price (2004) study as well as in the field screening work reported in James (2003 b) and James (2005) when undiluted MeSA was used to bait sticky traps.

Given the earlier non-responsiveness of *Anagrus* spp. and *Metaphycus* sp. to MeSA, MeJA and HA-baited sticky cards, it is possible that the positive responses to grapevine blocks baited with these HIPV reported here, may have been mediated by plant-signaling. Dispersion of MeSA, MeJA or HA volatiles in the vineyard may have signaled the plants to produce their own HIPV blend(s) which attracted *Anagrus* spp. and *Metaphycus* sp. James and Price (2004) suggested that the attraction of a wide variety of insect families to synthetic MeSA deployed in controlled-release dispensers in a vineyard experiment (Chrysopidae, Hemerobiidae, Coccinellidae, Geocoridae, Anthocoridae, Miridae, Syrphidae, Braconidae, Empididae, Sarcophagidae), was also perhaps a consequence of gaseous MeSA acting as a plant signal. Complete blends of natural HIPV from plants would be expected to attract a wider spectrum of pest natural enemies than synthetic MeSA alone.

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Evidence of a signaling function for MeSA, MeJA and HA in helping plants to recruit 'bodyguards' does exist. Rodriguez-Saona *et al.* (2001) in laboratory studies showed that cotton plants exposed to gaseous MeJA emitted elevated levels of volatiles similar but not identical, to those produced by plants exposed to herbivore attack. Shimoda *et al.* (2002) provided evidence that gaseous MeSA elicits the production of volatiles from bean leaves that are attractive to a predatory thrips species. Arimura *et al.* (2001) demonstrated that gaseous HA induced the expression of defense genes in bean leaves and Engelberth *et al.* (2004) presented evidence of a 'priming' role of green leaf volatiles (GLV) including HA, which enabled corn seedlings to produce greater amounts of HIPV after herbivore attack, than seedlings not previously exposed to GLV. No published studies have shown signaling effects of gaseous MeSA, MeJA or HA in the field, but this is clearly a promising area of research. The current study while raising the possibility of plants stimulated to produce HIPV in the presence of synthetic MeSA, MeJA or HA, does not provide the evidence needed to confirm this. Measuring and analyzing the volatiles produced by grapevines and hops exposed or not exposed to synthetic HIPV should provide definitive evidence for the existence or not of this mechanism and such studies are planned.

The possible use of synthetic HIPV either as direct or indirect enhancers of natural enemy population levels in crops (Herbivore-Induced Plant Protection Odors: HIPPO), is an exciting prospect. Recent studies (James, 2003 a,b; 2005; James and Price 2004) as well as the present work have provided evidence for the potential use of synthetic HIPV as aids to enhancing conservation biological control in crop ecosystems. However, many questions surrounding the use of these materials in integrated pest management remain to be answered.

For example, what are the ecological consequences of providing synthetic HIPV to predators and parasitoids in the absence (or relative absence) of their prey? Will this ‘misinformation’ result ultimately in non-response by natural enemies to HIPV? As noted above, most if not all of the predatory insects attracted to synthetic MeSA are generalist-feeding species (James 2003 a,b; James 2005; James and Price 2004) and the misinformation issue may not be as important with these species as it might be to specialist parasitoid species like *Anagrus* spp. which only parasitize leafhoppers. Defining and understanding the mechanism(s) of attraction and recruitment of predatory and parasitic insects by synthetic HIPV, will be of paramount importance in the effective use of these materials in crop pest management. The data in this study suggest that using synthetic HIPV to signal plants to produce their own HIPV blends is a possibility, but more extensive laboratory and field experimentation is required before this can be confirmed. Optimal deployment (release rates, dispenser density) of synthetic HIPV for natural enemy recruitment and retention, will require a good understanding of the precise mechanisms mediating attraction of predators and parasitoids. Comprehensive studies are planned and will be reported in due course.

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