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Manipulating vineyard biodiversity for improved insect pest management: case studies from northern California

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SUMMARY

We present the results of our studies in organic vineyards in Mendocino and Sonoma Counties, California, in an effort to systematize the emerging lessons from our experience on vineyard biodiversity enhancement for ecologically-based pest management. In the Mendocino study, a vegetational corridor connected to a riparian forest channelled insect biodiversity from surrounding habitats into the vineyard, thus overcoming the restricted spatial limits to which the positive influence of adjacent vegetation on vineyard pest dynamics is usually confined. In addition, summer cover crops substantially enhanced biological control of leafhoppers and thrips, by breaking the virtual monoculture that vineyards become in the summer after winter cover crops dry out or are ploughed under. In the Sonoma vineyard, an island of flowering shrubs and herbs provided season-long flower resources and alternate preys/hosts for natural enemies, which slowly built up in the adjacent vineyard. The island acted as a push-pull system for natural enemies, enhancing their activity but confining them mostly to the adjacent vine rows. Planting strips of summer cover crops could be a strategy to overcome the push effect of the island.

INTRODUCTION

Typical grape production in California is done in monocultures which are expanding at a rapid rate (nearly 230,000 ha of grapes were grown in California in 2002) resulting in the simplification of the landscape. Since the onset of such simplification, farmers and researchers have been faced with a major ecological dilemma arising from the homogenization of vineyard systems: increased vulnerability of crops to insect pests and diseases which, as in the case of Pierce's disease, can be devastating when infesting uniform crop, large-scale monocultures (Hoddle 2004; Redak *et al.*, 2004).

The expansion of monocultures has decreased abundance and activity of natural enemies due to the removal of critical food resources and overwintering sites (Corbett and Rosenheim 1996). Many scientists are concerned that, with accelerating rates of habitat removal, the contribution to pest suppression by biocontrol agents using these

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habitats will decline (Sotherton 1984; Fry 1995). It is possible that many pest problems affecting today's vineyards have been exacerbated by such trends. About 20 million kg of active ingredients of pesticides are used annually in California vineyards to counteract such pest pressure. The environmental impact of such pesticide load can be serious (Pesticide Action Network North America 2005).

Concern about these problems has led many people to propose options to rectify this habitat decline by increasing the vegetational diversity of agricultural landscapes. There are many ways in which increased plant biodiversity can contribute to the design of pest-stable agroecosystems by creating an appropriate ecological infrastructure within and around vineyards (Altieri and Nicholls 2004; Gurr *et al.*, 2004). Biodiversity is crucial to crop defences: the more diverse the plants, animals and soil-borne organisms that inhabit a farming system, the more diverse the community of pest-fighting beneficial organisms (predators, parasitoids, and entomopathogens) the farm can support.

In California, farmers usually resort to two main strategies to enhance biodiversity on their vineyards.

- Many farmers manage resident floor vegetation or plant cover crops as a habitat management tactic in vineyards to enhance natural enemies. Reductions in mite and grape leafhopper populations have been observed in cover cropped systems (Flaherty 1969; Daane *et al.*, 1998). However, in many cases such biological suppression has not been sufficient from an economic point of view (Daane and Costello 1998; English-Loeb *et al.*, 2003).
- Other farmers manage vegetation surrounding fields to meet the needs of beneficial organisms: Several studies indicate that the abundance and diversity of entomophagous insects within a field is dependent on the plants species composition of the surrounding vegetation, and also on the spatial extent of its influence on natural enemy abundance, which is determined by the distance to which natural enemies disperse into the crop (Landis *et al.*, 2000). The role of riparian habitats, and especially of wild blackberry patches, near vineyards in enhancing the effectiveness of the wasp *Anagrus epos* in parasitizing the grape leafhopper is well known (Doutt and Nakata 1973). Based on this knowledge, Corbett and Rosenheim (1996) found that French prunes (*Prunus domestica*) adjacent to vineyards could also serve as overwintering sites for *A. epos*, and found higher leafhopper parasitism in grape vineyards with adjacent prune tree refuges.

Other strategies tested experimentally and used by very few farmers include:

- Designing corridors of plants that usher beneficials from nearby forests or natural vegetation to field centres (Nicholls *et al.*, 2001)
- Selecting non-crop plants grown as strips or islands in fields, whose flowers match beneficials' requirements (Gurr *et al.*, 2004).

All the above strategies provide alternative food (pollen and nectar) and refuge for predators and parasitoids, and increased natural enemy diversity and abundance in vineyards (Altieri and Nicholls 2004). In the last 7 years we have applied the above strategies to the design and management of organic vineyards in northern California. In this paper, we present the results from some of our previously published studies (Nicholls *et al.*, 2000; Nicholls *et al.*, 2001), complemented by data from a new case study, in an effort to systematize the emerging lessons from our experience on vineyard biodiversity enhancement for ecologically-based pest management.

Our earlier studies took advantage of an existing 600-m corridor with at least 65 flowering species, connected to a riparian forest that cut across a monoculture organic vineyard located in Hopland, Mendocino County, California. This setting allowed for testing the idea whether such a corridor served as a biological highway for the movement and dispersal of natural enemies into the centre of the vineyard. We were interested in evaluating if the corridor acted as a consistent, abundant and well-dispersed source of alternative food and habitat for a diverse community of generalist predators and parasitoids, allowing predator and parasitoid populations to develop in the area of influence of the corridor well in advance of vineyard pest populations. We also thought that the corridor would serve as a conduit for the dispersion of predators and parasitoids within the vineyard, thus providing protection against insect pests within the area of influence of the corridor by allowing distribution of natural enemies throughout the vineyard.

As the vineyard was also diversified with cover crops, a hypothesis tested in this study was that neutral insects (non-pest herbivores) and pollen and nectar in the summer cover crops provide a constant and abundant supply of food sources for natural enemies. This in turn decouples predators and parasitoids from a strict dependence on grape herbivores, allowing natural enemies to build up in the system, thereby keeping pest populations at acceptable levels. We tested this hypothesis and examined the ecological mechanisms associated with insect pest reduction when summer cover crops are planted early in the season between alternate vine rows.

Last year, studies capitalized on the existence of a 0.5-ha island planted with several species of shrubs and flowers in the middle of the Sonoma vineyard. This allowed us to monitor the movement throughout the season of various predator and parasitoid species from the island to various sectors of the vineyard.

METHODS

Mendocino County vineyard study

The field studies were conducted in two adjacent organic Chardonnay vineyard blocks (blocks A and B, 2.5 ha each) within the larger vineyard, with riparian forest vegetation to the north. The main difference between the two blocks is that block A was penetrated and dissected by a 600-m vegetation corridor with 65 different flower species, planted in 1998. Both blocks were yearly planted to winter cover crops every other row, receiving an average of 2 tons of compost per hectare and preventive applications of sulfur against *Botrytis* spp. and *Oidium* spp. Half of each block was kept free of ground vegetation by one spring and one late summer disking (monoculture vineyard). In April, every alternate row of the other two halves of both blocks (cover cropped vineyard) was undersown with a 30/70 mixture of sunflower and buckwheat. Buckwheat flowered from late May to July and, as the buckwheat senesced, sunflower bloomed from July to the end of the season.

Ten yellow and ten blue sticky traps were placed at different points within the vineyard at increasing distances from the corridor or the bare edge (rows 1, 5, 15, 25, 45) in blocks A and B, respectively, to monitor diversity and abundance of the entomofauna. Yellow sticky traps were used to monitor leafhoppers (*Erythroneura elegantula*), the egg parasitoid *A. epos* and various predator species. Blue sticky traps were mainly used to assess thrips (*Franklinella occidentalis*) and *Orius* populations (Nicholls *et al.*, 2001).

From April to September of each year of the study (1996 and 1997), relative seasonal abundance and diversity of phytophagous insects and associated natural enemies were monitored on the vines in both treatment plots. Ten yellow and ten blue sticky traps were placed in each of 10 rows selected at random in each block to estimate densities of adult leafhopper, thrips, *Anagrus* wasps, *Orius* sp. and other predators.

In the same rows where sticky traps were placed, grape leaves were visually examined in the field and the number of *E. elegantula* nymphs were recorded on 10 randomly selected leaves in each row. This sampling method was carried out in sections with and without cover crops, allowing rapid and reliably determination of the proportion of infested leaves, densities of nymphs, and rates of leafhopper egg parasitization by the *Anagrus* wasp. More detailed descriptions on the sampling methodology used in the studies can be found in Nicholls *et al.* (2000; 2001).

Sonoma County vineyard study

In 2003, new research was initiated at Benziger vineyard located in Glenn Ellen, Sonoma County, California. This 17-ha vineyard began conversion to biodynamics in 1997, and since 2001 it is one of the few certified biodynamic vineyards in North America. (For information on biodynamic certification procedures see http://www.demeter-usa.org.)

As part of a whole-farm biodiversity management strategy, a 0.5-ha island of flowering shrubs and herbs (*insectory*) (Table 1) was created at the centre of the vineyard. This *insectory* was planted to provide flower resources from early April to late September to beneficial organisms, including natural enemies of grape insect pests. From 19 April to 6 September 2004, 30 yellow sticky traps were replaced every two weeks within the vineyard. Ten traps were randomly placed inside the *insectory*. The remaining 20 traps were evenly located along two circles centered around the *insectory*: ten traps at 30 m, and ten traps at 60 m from the *insectory*.

Table 1 List of *insectory* plants with brief description

Name	*Family*	*Origin*	*Common name*	*Wildlife value*
Agave americana	Agavaceae	Mexico	Century plant	Edible, pollen, seeds
Cordyline australis	Agavaceae	New Zealand	Palm lily	Habitat, nectar
Hesperaloe parviflora	Agavaceae	Texas (USA) and Mexico	Texas red yucca	Nectar
Yucca gloriosa	Agavaceae	North Carolina to Florida (USA)	Spanish dagger	Habitat, nectar, pollen
Yucca rostrata	Agavaceae	Mexico	Beaked yucca	Habitat, nectar, pollen, seeds
Aloe striata	Asphodelaceae	South Africa	Coral aloe	Nectar
Achillea filipendulina	Asteraceae	Northern Hemisphere	Moonshine yarrow	Nectar, seeds
Aster frikartii	Asteraceae	Europe	Monch	Nectar, pollen, seeds
Aster novi-belgii	Asteraceae	USA	Common aster	Nectar, pollen, seeds
Echinacea purpurea	Asteraceae	North America	Purple coneflower	Nectar, pollen, seeds
Erigeron karvinskianus	Asteraceae	Mexico	Mexican daisy	Nectar
Helianthus maximiliani	Asteraceae	North America	Perennial sunflower	Nectar, pollen, seeds
Ratibida columnifera	Asteraceae	New Mexico (USA)	Prairie coneflower	Nectar, seeds
Rudbeckia fulgida	Asteraceae	USA	Black-eyed Susan	Nectar, pollen, seeds
Senecio mandraliscae	Asteraceae	South Africa	Groundsel	Nectar, pollen, seeds
Echium fastuosum	Boraginaceae	Madeira	Pride of Madeira	Pollen
Anigozanthos sp.	Haemodoraceae	Western Australia	Kangaroo paw	Nectar
Crocosmia masonorum	Iridaceae	South Africa	Monbretia	July–September
Agastache rupestris	Labiatae	Southwestern USA and Mexico	Sunset hyssop	Nectar
Nepeta faassenii	Labiatae	Europe, Iran, Himalayas	Blue catmint	Nectar, seeds
Perovskia atriplicifolia	Labiatae	Deserts of Afghanistan	Russian sage	Pollen, seeds
Salvia greggii	Labiatae	Mexico and Southern USA	Autumn sage	Habitat, nectar, pollen, seeds
Salvia leucantha	Labiatae	Mexico	Mexican sage	Habitat, nectar, pollen, seeds
Kniphofia uvaria	Liliaceae	South Africa	Red hot poker	Nectar, seeds
Callihroe involucrata	Onagraceae	Southwest Asia	Wine cups	Pollen
Gaura lindheimeri	Onagraceae	Texas (USA)	Whirling butterfly	Nectar
Zauschneria garrettii	Onagraceae	California (USA)	Orange carpet	Nectar
Brahea armata	Palmae	Baja California (Mexico)	Blue hesper palm	Habitat, pollen, seeds
Butia capitata	Palmae	Argentina	Jelly palm	Habitat, pollen, seeds
Phoenix dactylifera	Palmae	North Africa	Date palm	Habitat
Penstemon pinifolius	Scrophulariaceae	Southern California	Desert beard tongue	Nectar
Penstemon eatonii	Scrophulariaceae	Utah	Firecracker penstemon	Nectar
Verbascum bombiciferum	Scrophulariaceae	Asia Minor	Arctic summer	Nectar, seeds

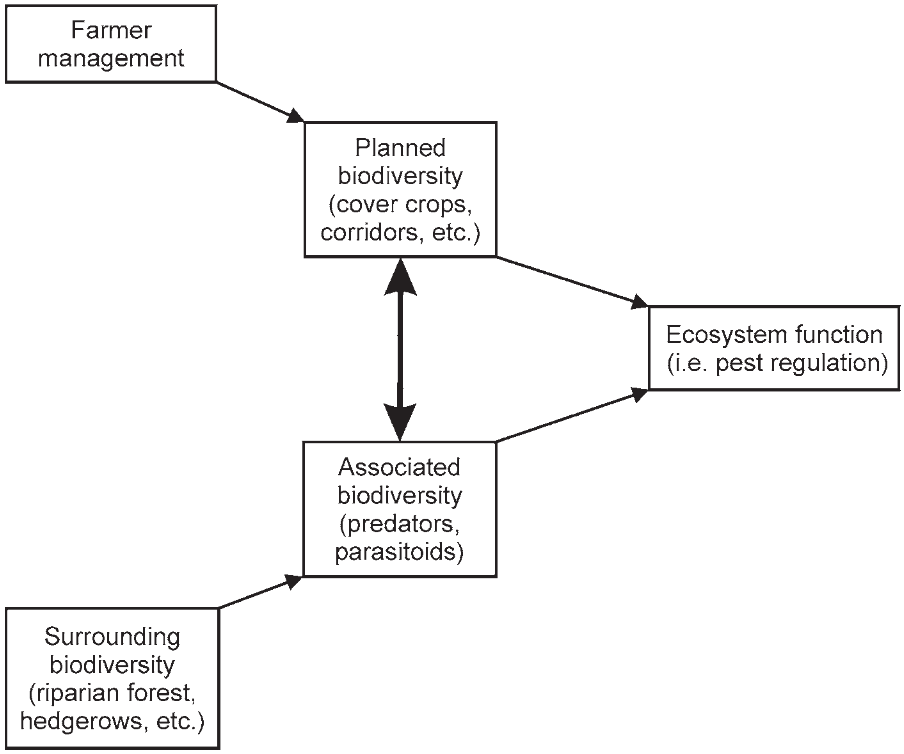

Figure 1 Relationship between several types of biodiversity and their role in pest regulation in a diversified vineyard

Grape leaf samples were also observed under a dissection microscope to check for egg parasitization and nymph population densities of *E. elegantula*. After sampling, grape leaves were immediately refrigerated and taken to the laboratory for observation. Leaf sampling was carried out on 12 July (n = 240), 26 July (n = 240), and 23 August (n = 360). In each date, half of the grape leaves were taken in the second vine row adjacent to the *insectory*, and half in the tenth row away from the *insectory* (ca. 25 m distance). Leaves were taken from the middle-basal portion of the shoots of randomly chosen vines in these rows.

RESULTS AND DISCUSSION

Biodiversity in vineyards and its function

Biodiversity in farms refers to all plants and animals (crops, weeds, livestock, natural enemies, pollinators, soil fauna, etc.) present in and around farms (McNeely *et al.*, 1990). The diversity of the vegetation within and around the farm, how many cover crops grown, and the proximity of the farm to a forest, hedgerow, meadow or other natural vegetation, are all factors that contribute to the biodiversity of a particular vineyard.

Two distinct components of biodiversity can be recognized in agroecosystems (Vandermeer and Perefecto 1995). The first component, *planned biodiversity*, includes the crops and other plants purposely included in the vineyard by the farmer. The second component, *associated biodiversity*, includes all soil flora and fauna, herbivores, carnivores, decomposers, etc. that colonize the agroecosystem from surrounding environments and that will thrive in the vineyard depending on its management and structure.

Based on our research, the relationship of both types of biodiversity components within vineyards is illustrated in Figure 1. Planned biodiversity has a direct function, as illustrated by the bold arrow connecting the planned biodiversity box with the ecosystem function box. Associated biodiversity also has a function, but it is mediated through the indirect function of planned biodiversity. For example, cover crops enrich the soil, which helps vine growth. The direct function of the cover crops is therefore to enhance soil fertility. Yet, the cover crops also provide habitat for wasps that seek out the nectar in the cover crop flowers. These wasps, in turn, are the natural parasitoids of pests that normally attack the vines. The wasps are part of the associated biodiversity. Thus, the cover crops both enrich the soil (direct function) and attract wasps (indirect function).

The challenge for farmers is to identify the aspects of biodiversity that are desirable to maintain and/or enhance in their farms in order to carry out specific ecological services (e.g. pest regulation) and then determine the best practices that will encourage such biodiversity (Altieri 1995; Gliessman 1998). In our research, we explored three biodiversity enhancing strategies (cover crops, corridor and insectory island) and report herein the results of the impact of such agroecological interventions on the dynamics of insect pests and associated natural enemies.

Mendocino vineyard studies

Enhancing within vineyard biodiversity with cover crops

Because most farmers either mow or plough under cover crops in the late spring, organic vineyards become virtual monocultures without floral diversity in early summer. It is important to maintain a green cover during the entire growing season in order to provide habitat and alternate food for natural enemies. An approach to achieve this is to sow summer cover crops that bloom early and throughout the season, thus providing a highly consistent, abundant and well-dispersed alternative food source, as well as microhabitats, for a diverse community of natural enemies (Nicholls *et al.*, 2000). Such food supply decouples predators and parasitoids from a strict dependence on grape herbivores, allowing an early build up of natural enemies in the system, which helps in keeping pest populations at acceptable levels.

Maintaining floral diversity throughout the growing season in the Mendocino vineyard in the form of summer cover crops of buckwheat and sunflower, reduced substantially the abundance of grape leafhoppers and thrips, while the abundance of associated natural enemies increased. In two consecutive years (1996– 1997), vineyard systems with flowering cover crops were characterized by lower densities of leafhopper nymphs and adults (Figure 2). Thrips also exhibited reduced densities in vineyards with cover crops in both seasons.

During both years, general predator populations on the vines were higher in the cover-cropped sections than in the monocultures. Generally, the populations were low early in the season and increased as prey became more numerous as the season progressed. Dominant predators included spiders, *Nabis* sp., *Orius* sp., *Geocoris* sp., Coccinellidae, and *Chrysoperla* sp..

Although *A. epos*, the most important leafhopper parasitoid wasp, achieved high numbers and

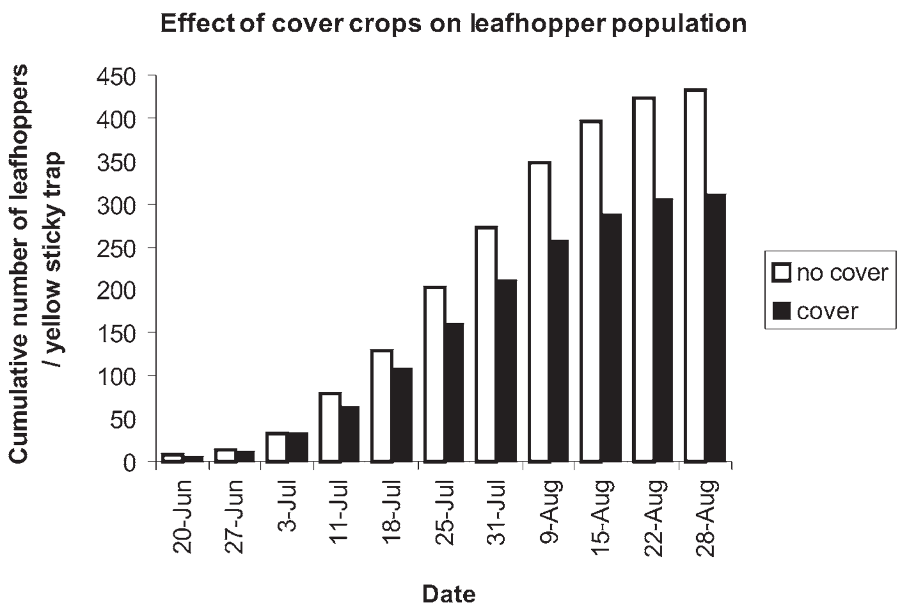

Figure 2 Densities of adult leafhoppers *E. elegantula* in cover cropped and monoculture vineyards in Hopland, California, during the 1996 and 1997 growing seasons

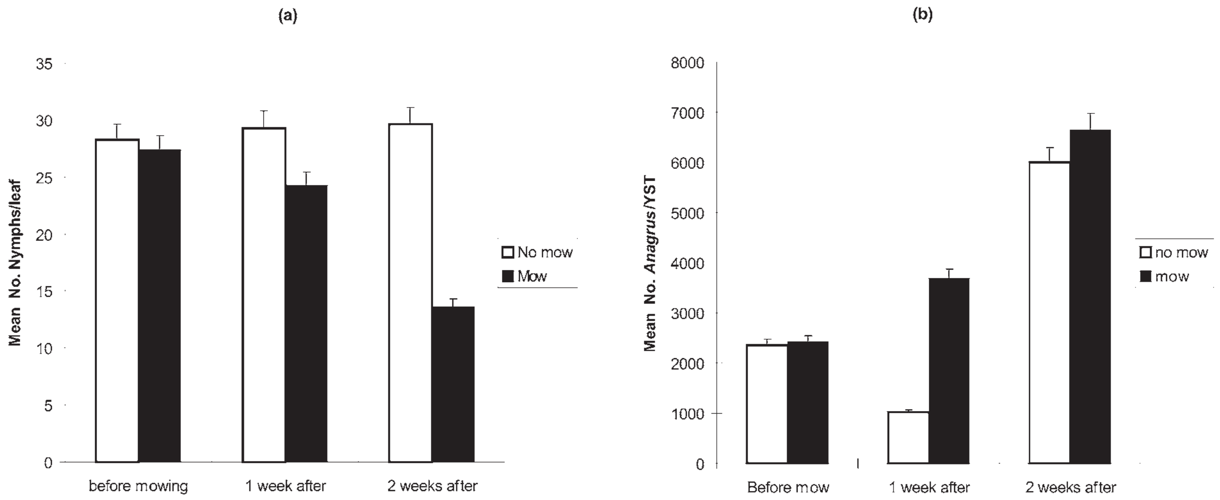

Figure 3 (a) Effect of cover crop mowing in vineyards on densities of leafhopper nymphs during the 1997 growing season in Hopland, California. (b) Effects of cover crop mowing in vineyards on densities of *Anagrus epos* during the 1997 growing season in Hopland, California

inflicted noticeable mortality on grape leafhopper eggs, this impact was not substantial enough. Apparently, the wasps encountered sufficient food resources in the cover crops and few moved to the vines to search for leafhopper eggs. For this reason, cover crops were mowed every other row to force movement of *Anagrus* wasps and predators into the vines. Before mowing, leafhopper nymph densities on vines were similar in the selected cover-cropped rows. One week after mowing, numbers of nymphs declined on vines where the cover crop was mowed, coinciding with an increase in *Anagrus* densities in mowed cover crop rows. During the second week such nymphal decline was even more pronounced, coinciding with an increase in numbers of *Anagrus* wasps in the foliage (Figure 3).

The mowing experiment suggests a direct ecological linkage, as cutting the cover crop vegetation forced the movement of the *Anagrus* and other predators harbored by the flowers, resulting in both years in a decline of leafhopper numbers on the vines adjacent to the mowed cover crops. Obviously, the timing of mowing must coincide with the time when eggs are present on the vine leaves in order to optimize the efficiency of arriving *Anagrus* wasps.

Corridor influences on population gradients of leafhoppers, thrips and associated natural enemies

Studies assessing the influence of adjacent vegetation or natural enemy refuges on pest dynamics within vineyards show that, in the case of prune refuges, the effect is limited to only a few vine rows downwind, as the abundance of the parasitoid *A. epos* exhibited a gradual decline in vineyards with increasing distance from the refuge. This finding poses an important limitation to the use of prune trees, as the colonization of grapes by *A. epos* is limited to field borders, leaving the central rows of the vineyard void of biological control protection. The 600-m corridor with at least 65 flower species, connected to a riparian forest and cutting across the Mendocino vineyard, was established to overcome this limitation.

Data collected within the corridor during the 1996 and 1997 growing seasons showed that species such as *Chrysoperla carnea*, *Orius* sp., *Nabis* sp., *Geocoris* sp., and several members of the families Coccinellidae, Syrphidae, Mordellidae and some species of thomisid spiders, were the predators commonly found on the flowers of the dominant corridor plants such as fennel (*Foeniculum vulgare*), yarrow (*Achillea millefolium*), *Erigeron annuus* and *Buddleja* spp. Certain predator species were continuously found associated with specific flowering plants (Figure 4).

The flowering sequence of the various plant species provided a continuous source of pollen and nectar, as well as a rich and abundant supply of neutral insects for the various predator species, thus allowing the permanence and circulation of viable populations of key species within the corridor.

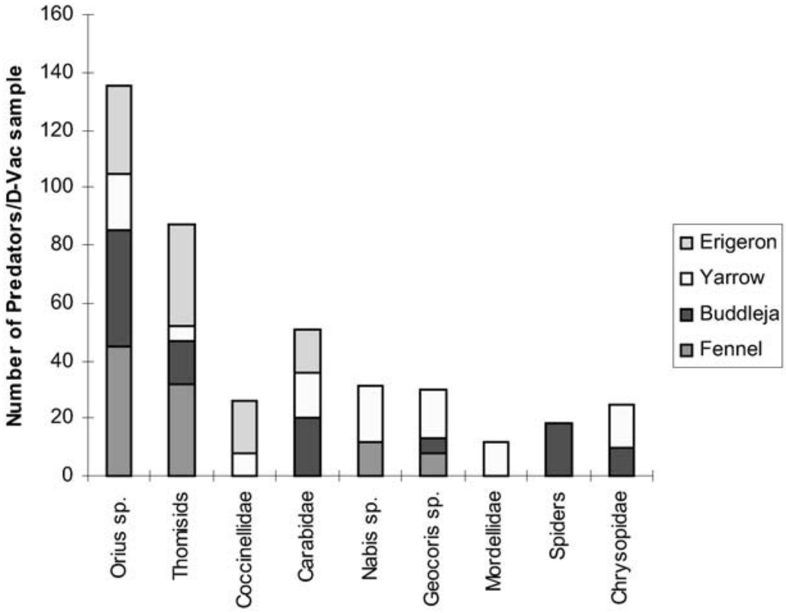

Figure 4 Main predator groups associated with dominant corridor flowering plants (Hopland, California 1996)

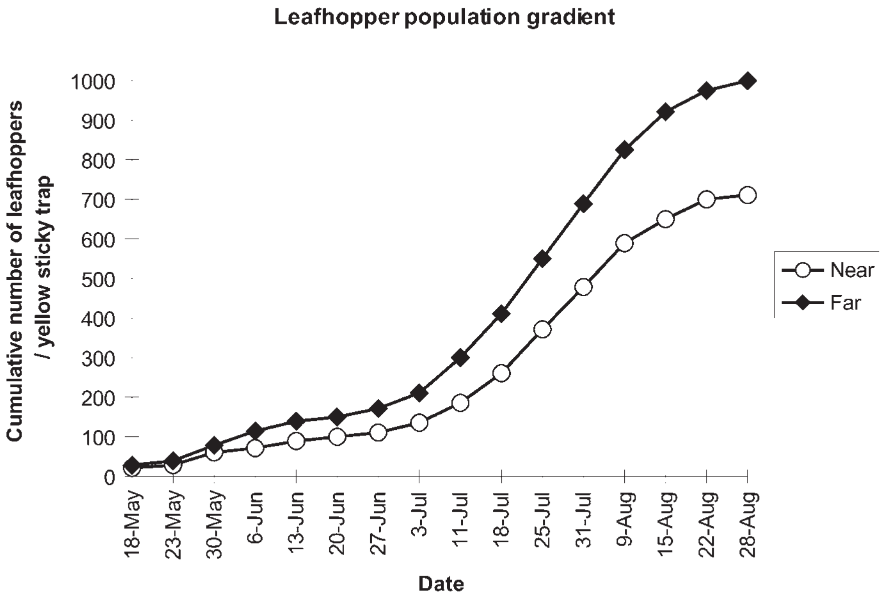

Figure 5 Seasonal patterns of adult leafhoppers in a vineyard near and far from the corridor (Hopland, California 1996)

In both years, adult leafhoppers exhibited a clear density gradient, with lowest numbers in vine rows near the corridor and increasing in numbers towards the centre of the field. The highest concentration of adult and nymph leafhoppers occurred after the first 20–25 rows (30–40 m) downwind from the corridor (Figure 5). A similar population and distribution gradient was apparent for thrips. In both years, leafhopper and thrip catches were substantially higher in the central rows than in rows adjacent to the corridor.

The abundance and spatial distribution of generalist predators in the families Coccinellidae, Chrysopidae, Nabidae and Syrphidae was influenced by the presence of the corridor which channelled dispersal of the insects into adjacent vines (Figure 6). Predator numbers were higher in the first 25 m adjacent to the corridor, which probably explains the reduction of leafhoppers and thrips observed in the first 25 m vine rows near the corridor. The presence of the corridor was associated with the early vineyard colonization by *Anagrus*

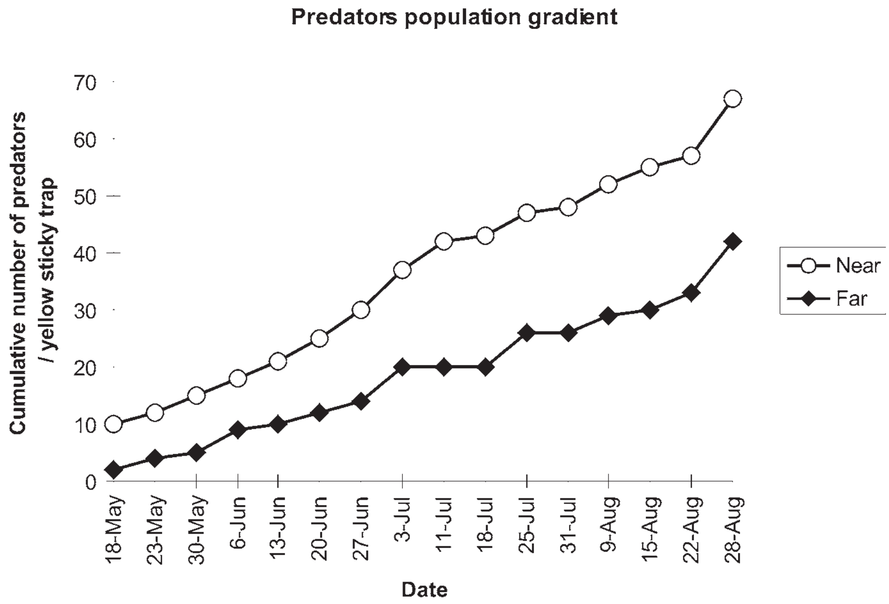

Figure 6 Seasonal patterns of predator catches (numbers per yellow sticky trap) in a vineyard, as influenced by the presence or absence of forest edge and the corridor ($p < 0.05$; Mann–Whitney U test) (Hopland, California 1996)

wasps, but this did not result in a net season-long prevalence in leafhopper egg parasitism rates in rows adjacent to the corridor. The proportion of eggs parasitized tended to be uniformly distributed across all rows in both blocks. Eggs in the centre rows had slightly higher mean parasitization rates than eggs located in rows near the corridor, although differences were not statistically significant.

Creating flowering islands as a push-pull system for natural enemies in a Sonoma vineyard

One good way to start integrating vineyard management and conservation of natural enemies is to develop a whole farm plan which recognizes the reality that not all parts of the farm can be managed to maximize conservation objectives. Cover crops, adjacent vegetation and corridors are all important, but creating habitat on less productive parts of the farm to concentrate natural enemies may be a key strategy. This is the approach used at Benziger farm in Sonoma County, where a 0.25-ha island of flowering shrubs and herbs was created at the centre of the vineyard to act as a push-pull system for natural enemy species.

The island and its mix of shrubs and herbs provides flower resources from early April to late September to a number of herbivore insects (pests, neutral non-pestiferous insects and pollinators)

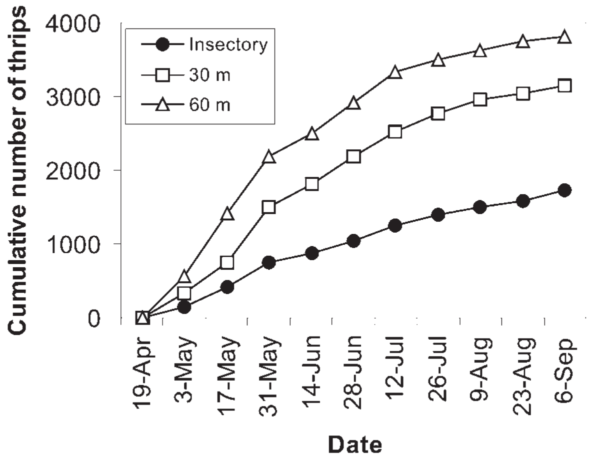

Figure 7 Cumulative number of thrips per yellow sticky trap in 2004 at Benziger vineyard (Glenn Ellen, California)

and associated natural enemies which build up in the habitat, with some of them dispersing into the vineyard. Clear population gradients were observed for thrips (the only pest species found in the *insectory*), which increased in abundance in vines farther away from the island (Figure 7).

Responding to the abundance of habitat resources in the *insectory*, predators tended to decrease in abundance in vines 30 or 60 m away (Figure 8). *Orius* reached significantly lower abundances in vines away from the *insectory*, a trend that correlated with the densities of thrips displayed in Figure 7.

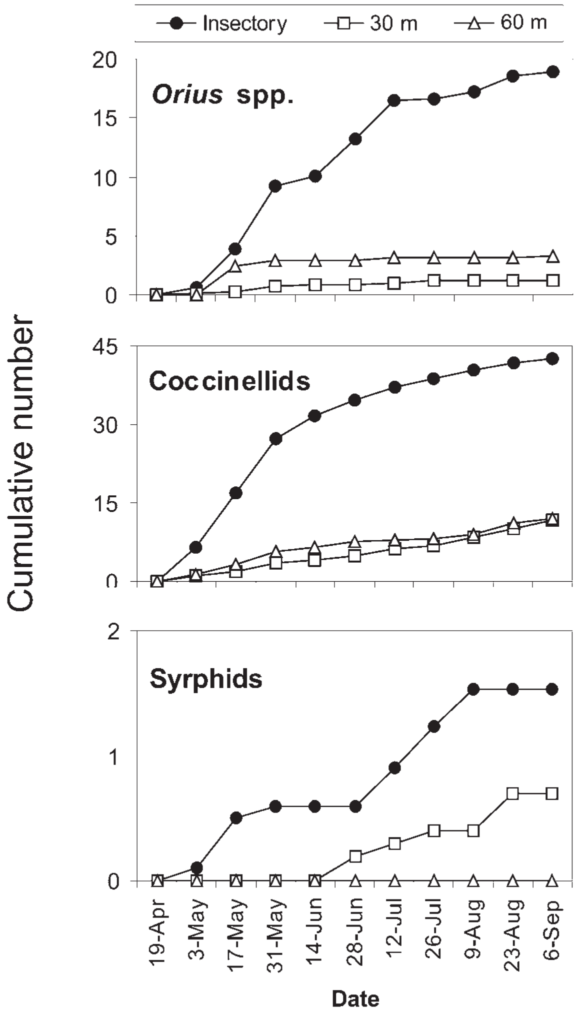

Figure 8 Cumulative number of *Orius* spp, Coccinellids and Syrphids per yellow sticky trap in 2004 at Benziger vineyard (Glenn Ellen, California)

As seen in Figure 9, the island acts as a source of pollen, nectar and neutral insects which serve as alternate food to a variety of predators and parasites, including *Anagrus* wasps. The island is dominated by neutral insects that forage on the various plants but also serve as food to natural enemies, which slowly build up in numbers in the adjacent vineyard as the season progresses. Many natural enemies moved from the island into the vineyard (up to 60 m). While the proportion of natural enemies in relation to the total number of insects caught in the traps remained relatively constant within the *insectory*, their proportion increased from 1% to 10 or 13% in vines located 30 m or 60 m from the *insectory*, respectively. *Orius* spp. and Coccinellids are prevalent colonizers at the beginning of the season, but later syrphid flies and *Anagrus* wasps start dispersing from the island (*insectory*) into the vineyard (Figure 10).

Table 2 Levels of leafhopper eggs parasitization by *Anagrus* wasps in the second and tenth vine rows from the island during the peak summer months (Glenn Ellen, California, 2004)

	% parasitization	
Date	*2nd row*	*10th row*
12 July	76.8	54.1
26 July	52.4	52.3
23 August	43.6	32.1

Parasitization of leafhopper eggs by *Anagrus* wasps was particularly high on the vines near the island (10 m from the island), with parasitization levels decreasing slightly around the 10th row (40 m) and decreasing even more towards the centre of the vineyard, away from the island (Table 2). It is possible that the presence of pollen and nectar in the island flowers build up the populations of *A. epos*, which moved from the island, confining their activity to nearby rows.

The next step in our research will be to plant flower strips (of *Phacelia*, *Alyssum*, buckwheat) in selected rows that go from the island into the vineyard, to assess if this might be an effective way to pull *Anagrus* and other beneficial species deeper into the vineyard and thus overcome the push effect of the island which confines natural enemy activity to the adjacent vine rows.

CONCLUSIONS

A key strategy in sustainable viticulture is to enhance biodiversity at the landscape and field level through the use of cover crops, corridors and various habitats. Emergent ecological properties that develop in such diversified vineyards allow the system to function in a self-regulating manner. The main approach in ecologically-based pest management is to increase agroecosystem diversity and complexity as a foundation for establishing beneficial interactions that keep pest population in check (Gurr *et al.*, 2004).

Diverse and complex vineyards may be harder to manage, but when properly implemented, habitat management leads to the establishment of the desired type of plant biodiversity and a unique ecological infrastructure necessary for attaining

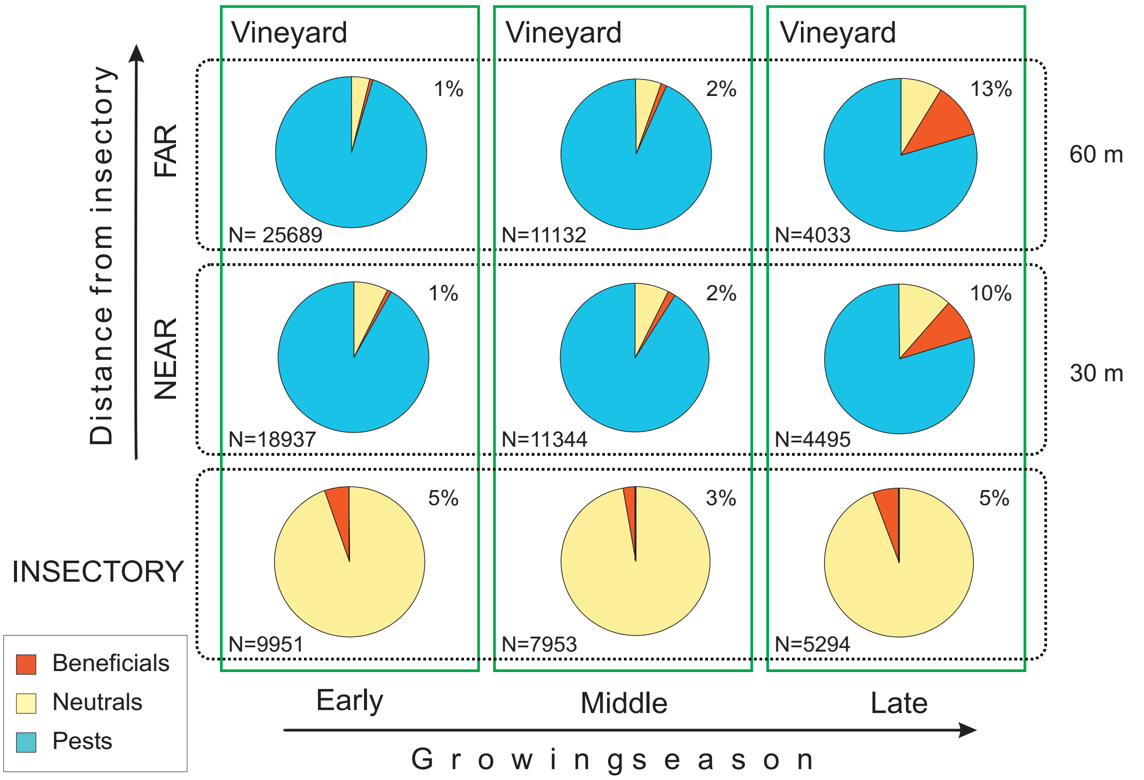

Figure 9 The proportion of beneficial, neutral, and pestiferous insects in the island, and in the vineyard at various distances from the island as the season progressed (N = total number of insects caught in the yellow sticky traps, % = proportion of beneficial insects) (Glenn Ellen, California 2004)

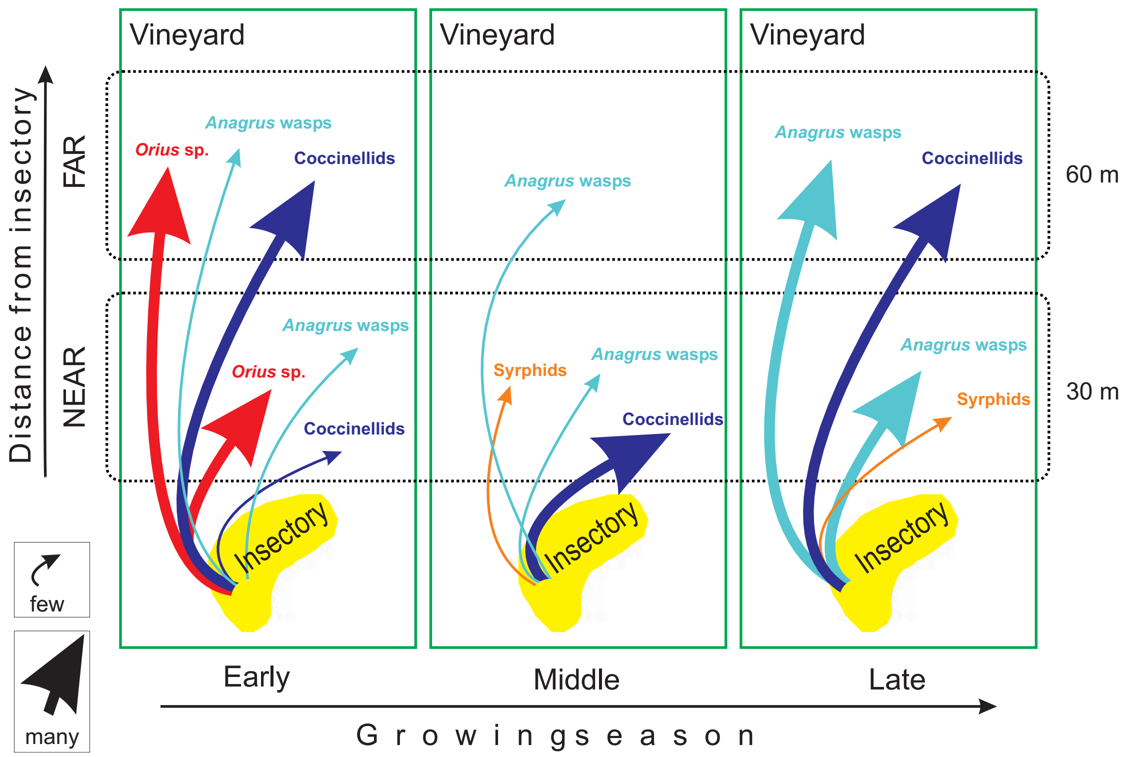

Figure 10 Dispersal of *Anagrus* wasps and generalist predators from the island into the vineyard (Glenn Ellen, California 2004)

optimal natural enemy diversity and abundance. A key feature of that infrastructure is flower resources. When choosing flowering plants to attract beneficial insects, it is important to note the size and shape of the blossoms, because these dictate which insects will be able to access the flowers' pollen and nectar. For most beneficial species, including parasitic wasps, the most helpful blossoms should be small and relatively open. Plants from the Compositae and Umbelliferae families are especially useful.

Timing of flower availability is as important to natural enemies as blossom size and shape. Many beneficial insects are active only as adults and only for discrete periods during the growing season; they need pollen and nectar during these active times, particularly in the early season when prey are scarce. One of the easiest approaches is for farmers to provide beneficial species with mixtures of plants with relatively long, overlapping bloom times.

Current knowledge of which plants are the most useful sources of pollen, nectar, habitat, and other critical needs is far from complete. Clearly, many plants encourage natural enemies, but there is much more to learn about which plants are associated with which beneficial species and how and when to make desirable plants available to target organisms. In addition, since beneficial species interactions are site-specific, geographic location and overall farm management are critical variables to consider when selecting insectory plants to enhance specific natural enemy guilds.

To design an effective plan for successful habitat management, farmers should first gather as much information as they can, including making a list of the most economically important pests and their associated natural enemies on the farm and finding out:

- What are the pest's food and habitat requirements?
- What factors influence pest abundance?
- When do pests build in the crop and when do they become economically damaging?
- What are the most important predators, parasites, and pathogens?
- What are the primary needs of those beneficial organisms?
- Where do these beneficials overwinter, when do they appear in the field, where do they come from, what attracts them to the crop, how and when do they build up in the crop, and what keeps them in the field?
- When do the critical resources (nectar, pollen, and alternative hosts and prey) for beneficial species appear and how long are they available? Are alternate food sources accessible nearby and at the right times? Which native annuals and perennials can compensate for critical gaps in timing, especially when prey are scarce?

Once farmers have a thorough knowledge of the characteristics and needs of key pests and natural enemies, they are ready to begin designing a habitat management strategy specific for their farm. A few guidelines need to be considered when implementing habitat management strategies:

- Select the most appropriate plant species;
- Determine the most beneficial spatial and temporal arrangement of such plants, within and/or around the fields;
- Consider the spatial scale at which the habitat enhancement operates (e.g., field or landscape level);
- Understand the predator-parasitoid behavioral mechanisms influenced by the habitat manipulation;
- Anticipate potential conflicts that may emerge when adding new plants to the agroecosystem (e.g. in California, blackberries, *Rubus* sp., around vineyards increase populations of the wasp *A. epos*, a parasotoid of the grape leafhopper *Erythroneura* spp., but can also enhance abundance of the sharpshooter, which serves as a vector of Pierce's disease);
- Develop ways in which the added plants do not upset other agronomic management practices, and select plants that have multiple effects, such as improving pest regulation while, at the same time, contributing to soil fertility and weed suppression.

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REFERENCES

Altieri MA. *Agroecology: the science of sustainable agriculture.* Boulder, CO: Westview Press; 1995

Altieri MA and Nicholls CI. *Biodiversity and pest management in agroecosystems.* Binghamton USA: Food Products Press; 2004

Corbett A and Rosenheim JA. Impact of a natural enemy overwintering refuge and its interaction with the surrounding landscape. *Ecological Entomology* 1996;2(2):155–64

Daane KM and Costello MJ. Can cover crops reduce leafhopper abundance in vineyards? *California Agriculture* 1998;52(5):27–33

Daane KM, Costello MJ, Yokota GY and Bentley WJ. Can we manipulate leafhopper densities with management practices? *Grape Grower* 1998;30(4): 18–36

Department of Pesticide Regulation. *Summary of Pesticide Use Report Data 2003.* Sacramento, CA, USA: Department of Pesticide Regulation; 2003

Doutt RL and Nakata J. The *Rubus* leafhopper and its egg parasitoid: an endemic biotic system useful in grape-pest management. *Environmental Entomology* 1973;2(3):381–6

English-Loeb G, Rhainds M, Martinson T and Ugine T. Influence of flowering cover crops on *Anagrus* parasitoids (Hymenoptera: Mymaridae) and *Erythroneura* leafhoppers (Homoptera: Cicadellidae) in New York vineyards. *Agricultural and Forest Entomology* 2003;5(2):173–81

Flaherty DL. Ecosystem complexity and the Willamette mite, *Eotetranychus willamettei* (Acarine: Tetranychidae) densities. *Ecology Letters* 1969;50: 911–16

Fry GLA. Landscape ecological principles and sustainable agriculture. Integrated crop protection: towards sustainability? Proceedings of a symposium, Edinburgh, UK 1995:247–54

Gliessman SR. *Agroecology: ecological processes in sustainable agriculture.* Chelsea USA: Ann Arbor Press; 1998

Gurr GM, Wratten SD and Altieri MA. *Ecological engineering for pest management: advances in habitat manipulation for arthropods.* Wallingford UK: CABI Publishing; 2004

Hoddle MS. The potential adventive geographic range of glassy-winged sharpshooter, Homalodisca coagulata and the grape pathogen *Xylella fastidiosa*: implications for California and other grape growing regions of the world. *Crop Protection* 2004; 23(8):691–9

Landis DA, Wratten SD and Gurr GM. Habitat management to conserve natural enemies of arthropod pests in agriculture. *Annual Review of Entomology* 2000;45:175–201

McNeely JA, Miller KR, Reid WV, Mittermeier RA and Werner TB. *Conserving the world's biological diversity.* Gland Switzerland: International Union for Conservation of Nature and Natural Resources; 1990

Nicholls CI, Parrella MP and Altieri MA. Reducing the abundance of leafhoppers and thrips in a northern California organic vineyard through maintenance of full season floral diversity with summer cover crops. *Agricultural and Forest Entomology* 2000;2(2):107–13

Nicholls CI, Parrella M and Altieri MA. The effects of a vegetational corridor on the abundance and dispersal of insect biodiversity within a northern California organic vineyard. *Landscape Ecology* 2001;16(2):133–46

Redak RA, Purcell AH, Lopes JRS, Blua MJ, Mizell RF, III and Andersen PC. The biology of xylem fluid-feeding insect vectors of *Xylella fastidiosa* and their relation to disease epidemiology. *Annual Review of Entomology* 2004;49:243–70

Sotherton NW. The distribution and abundance of predatory arthropods overwintering on farmland. *Annals of Applied Biology* 1984;105(3):423–9

Vandermeer J and Perefecto I. *Breakfast of biodiversity.* Oakland, CA: Food First Books; 1995