Chapter 19

COVER CROPS AND RELATED METHODS FOR ENHANCING AGRICULTURAL BIODIVERSITY AND CONSERVATION BIOCONTROL: SUCCESSFUL CASE STUDIES

P.G. Tillman, H.A. Smith and J.M. Holland

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INTRODUCTION

In modern agricultural systems mechanical cultivation and chemical pesticides are used for crop production, restricting diversity and promoting landscapes dominated by large monocultures. Through the use of equipment such as harrows and mowers, large portions of the biomass are often removed and/or tilled annually, thereby forcing the growth process to start over. Herbicides are used to manage weeds, and fertilisers are used to foster rapid, lush growth of the crop. The prevailing insect pest control strategy in these agricultural systems is application of toxic agrochemicals. Such prophylaxis 'insurance' approaches can lead to biological control failure or a least a reduction in effectiveness as a result of the direct and indirect effects of pesticides, tillage, cultivation, lack of nectar and pollen sources, scarcity of hosts and lack of shelter and hibernation, mating and oviposition sites (Corbett and Rosenheim, 1996; Landis *et al*., 2000; Heimpel and Jervis, 2005). In the absence of vital resources, colonisation by predatory species is often much lower than that by herbivores (Altieri and Whitcomb, 1979; Thies and Tscharntke, 1999), resulting in the failure of predators and parasitoids to control pests as they begin colonising crops (Landis *et al*., 2000). Long-term solutions to escalating economic and environmental consequences of combating pests in agricultural crops can be achieved by restructuring and managing agroecosystems in ways that enhance agricultural diversity to increase biocontrol and other ecological services for pest management.

One of the most important aspects of enhancing biodiversity in agricultural systems involves the provision of resources for natural enemies of pest insects and insect pollinators. Interestingly, many of the habitats incorporated into agricultural systems for enhancing natural enemies are multifunctional, for they can provide other ecological benefits such as conserving wildlife, protecting water quality and reducing erosion and runoff (Leidner and Kidwell, 2000; Thomas *et al*., 2001; SWCS, 2006; Triplett and Dick, 2008; FAO, 2010). Understanding the ecology of insect pests and their natural enemies in agroecosystems is essential in creating and designing habitats for enhancing agricultural biodiversity for pest suppression. It is important to have a clear understanding of what resources are needed and how specific habitats can successfully provide these resources. Strategic placement, in time and space, of a multifunctional habitat in an agricultural system may also be essential for successfully increasing biocontrol and other ecological services for pest management. For example, the southern green stinkbug (*Nezara viridula* L.) is a generalist feeder that exhibits edge-mediated dispersal from peanut into cotton at the common boundary of the two crops in peanut–cotton farmscapes (Tillman *et al*., 2009). Addition of a habitat of sorghum along this boundary apparently enhances biocontrol of this pest by the adult fly *Trichopoda pennipes* F. (Tachinidae) (Tillman, 2006). Strategic establishment of a corridor composed of 65 flowering plant species enhanced predator colonisation and abundance on adjacent organic vineyards by providing timely circulation and dispersal of predators into the centre of the field (Nicholls *et al*., 2001).

In this chapter, we present three examples of establishing a habitat in an agricultural system at the right time and location for enhancement of agricultural biodiversity and conservation biocontrol. These include use of cover crops and conservation tillage in cotton fields, provision of insectary plants within lettuce fields and establishment of beetle banks within cereal fields. For each of these examples we cover the driving forces that led to the introduction of a biodiversity-based pest management system, discuss the development of the habitat and evaluate its effectiveness and uptake, while providing some information on the economics.

COVER CROPS AND CONSERVATION TILLAGE IN COTTON IN GEORGIA, USA

Cotton, *Gossypium hirsutum,* is a fibre, feed and food crop. The fibre of cotton is used to make thousands of products including T-shirts, sheets, towels, etc. US textile mills spun over 3.5 million bales of cotton in 2010 (NCC, 2011), enough cotton fibre to make over 1 billion pairs of jeans. About 70% of the harvested crop is composed of the seed, which is crushed to separate its three products – oil, meal and hulls. Cotton seed oil is a common component of many food items, used primarily as a cooking oil, shortening and salad dressing. The oil is used extensively in the preparation of such snack food as crackers, cookies and chips (crisps). The meal and hulls are used as livestock, poultry and fish feed.

Traditionally cotton is one of the most pest-plagued, and thus one of the most pesticide-treated, commodities. Many of the pesticides used in conventional cotton production can adversely impact human and animal health and the environment both directly and indirectly. Indeed, a study conducted by researchers at the Technical University of Lódz in Poland has shown that hazardous pesticides applied during cotton production can sometimes be detected in cotton clothing (EJF, 2007). In California, the leaves, stems, and short fibres of cotton known as 'gin trash' can contain concentrated levels of pesticide residue, making it illegal to feed this cotton by-product to livestock (Maan and Beam, 2009). Highly toxic insecticides used to control cotton insect pests can kill their natural enemies which may lead to a resurgence of the pests or outbreaks of secondary pests. For example, heavy outbreaks of beet armyworms (*Spodoptera exigua* (Hübner) can be generated by insecticide treatments used to suppress the plant bug (*Lygus Hesperus* Knight) in cotton (Eveleens *et al.*, 1973). Biodiversity-based pest management systems are needed to reduce use of pesticides in cotton production.

Georgia is one of the leading cotton-producing states in the US; over 1.3 million bales were harvested there in 2010 (Williams, 2011). In Georgia cotton is planted in early summer and harvested in the fall. Since the eradication of the boll weevil (*Anthonomus grandis* Boheman), larvae of the heliothines, the tobacco budworm (*Heliothis virescens* F. and the cotton bollworm (*Helicoverpa zea* (Boddie), and nymphs and adults of the stinkbugs, the southern green stinkbug, the brown stinkbug (*Euschistus servus* (Say), and the green stinkbug (*Chinavia hilaris* (Say), have been the two major pest complexes causing economic damage to cotton in this state.

Many farmers in Georgia became increasingly interested in conservation tillage as research efforts began demonstrating that it could work with cover cropping to improve soil quality and long-term soil productivity, reduce soil erosion, promote beneficial insects and provide greater agroecosystem stability (Blumberg and Crossley, 1982; McPherson *et al.*, 1982; Sprague and Triplett, 1986; Triplett, 1986; Guthrie *et al.* 1993). Thus, from the mid-1990s grower-driven research was conducted in the southern region of the state to determine the effects of a legume, crimson clover (*Trifolium incarnatum* L.), and a grass, rye (*Secale cereal* L.), cover crop in a conservation-tillage system on the populations of insect pests and their natural enemies in non-*Bt* cotton. In these experiments, primarily the heliothines reached economic threshold (i.e. pest level at which a control measure should be applied to prevent economic damage), which is a 5% infestation of first instars on cotton plants. Either equal or fewer insecticide applications were needed for control of these pests in the cover crop/conservation-tilled fields compared to the conventional ones (Ruberson *et al.*, 1995; Lewis *et al.*, 1996; Ruberson *et al.*, 1997).

Building on the work of previous researchers, a group of research scientists funded by SARE (Sustainable Agriculture Research and Education) initiated a two-year cover/conservation tillage on-farm experiment in non-*Bt* cotton in Georgia in the fall of 2000 (Tillman *et al.*, 2004). The main insect research goal was to develop an early-season habitat for natural enemies of pests that would promote biological control of these pests in cotton and minimise the need for insecticides without sacrificing yield. The five cover crop treatments were 1) rye (standard grass cover crop), 2) crimson clover (standard legume cover crop), 3) a legume cover crop mix of balansa clover (*Trifolium michelianum* Savi), crimson clover and hairy vetch (*Vicia villosa* Roth.), 4) a combination of the legume cover crop mix plus rye and 5) no cover crop (Figure 19.1). The legume cover crop mix of an early- (balansa clover), mid- (crimson clover) and late- (hairy vetch) spring flowering legume was used to extend the availability of the habitat and the provision of nectar to insect pollinators in the field beyond what could be attained using a single legume species. For the legume and rye treatment, alternating strips of the legume mix and rye were planted to combine the benefits of a legume habitat and nitrogen fixation with the enhanced biomass production of rye. The rye and legume mix were planted so that a strip of rye grew in the centre of the future cotton row, and strips of the legume mix grew between the rows. All cover crops were killed approximately three weeks before planting the cotton. Legume cover crops were strip-killed by applying an herbicide in a 46–53 cm-wide strip of cover crop in the centre of the future cotton row. The tallness of rye made it difficult to maintain row patterns in this cover crop, and so it was broadcast-killed. While planting cotton, the soil was strip-tilled in the band of dead legume cover crop or in the centre of the row for the dead rye. In control fields with no cover crop, conventional tillage practices were used for cotton production.

The heliothine complex was the only group of insect pests that caused economic damage to cotton in both years of the study. Cotton bollworms and tobacco budworms only cause damage to cotton in the larval (worm) stage. First instars feed on plant terminals and

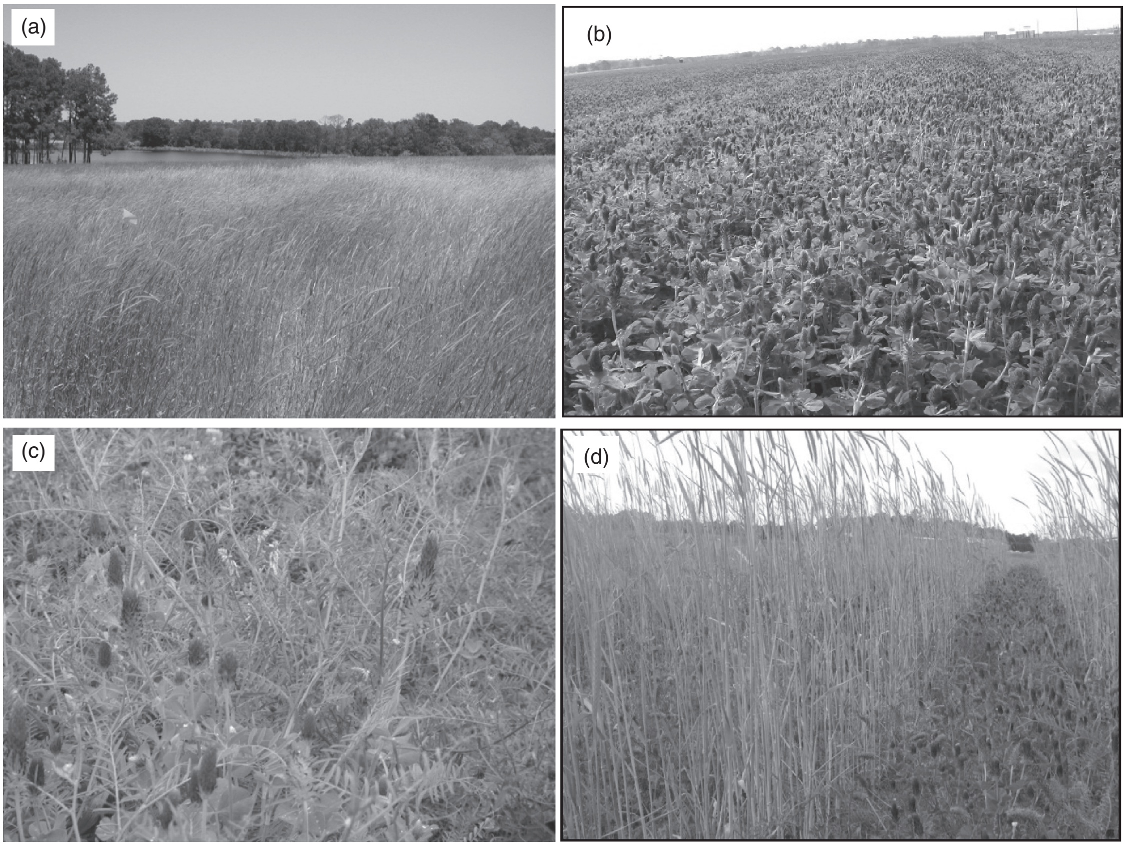

Figure 19.1 Winter cover crops used to promote biological control in cotton: a) rye, (b) crimson clover, c) legume mixture, and d) legume mixture + rye (K.J. Graham).

small squares (buds) and may sometimes destroy the terminal bud, which results in branching of the plant. Later instars move into lower squares, blooms and then bolls (fruit). These larvae burrow into squares and bolls, often hollowing them out. A single larva feeds on 6 to 7 squares and 2 to 3 bolls during its developmental period. Injured squares are often shed. Bolls that are fed upon do not produce cotton fibre or seed.

Big-eyed bugs, *Geocoris punctipes* (Say), pirate bugs, *Orius insidiosus* Say and red imported fire ants, *Solenopsis invicta* Buren, preyed on eggs and small larvae of these pests in both the cover crops and the cash crop. In the spring, the flowers of each legume species produced nectar and were visited frequently by bees and other insect pollinators. Also, predator populations built up in the cover crops, especially in the crimson clover and legume cover crop mix. Later, conservation tillage of these legume cover crops allowed a live strip of cover crop to remain between crop rows to serve as a habitat and food source for natural enemies until the cotton crop was established. Density of *G. punctipes* in crimson clover on the last sampling date was statistically similar to density of this predator in cotton on the first sampling date in 2001 (Figure 19.2) and in the legume cover crop mix in both years of the study. In 2002, density of *G. punctipes* was significantly higher in the first cotton sweeps compared to the last crimson clover sweeps. Evidently, intercropping cotton in strips of cover crop resulted in the relay of *G. punctipes* from these cover crops onto cotton.

Even though both nymphs and adults of *G. punctipes* are predatory, they fed on leaves of each cover crop

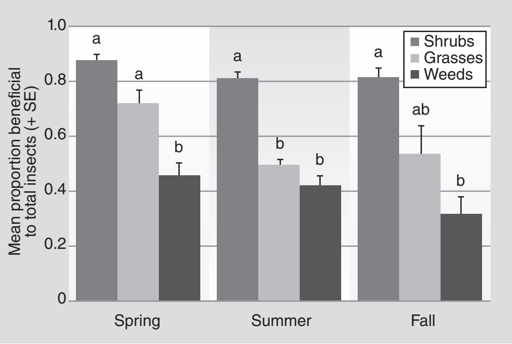

Figure 19.2 Seasonal occurrence of *Geocoris punctipes* in conservation-tillage cotton with crimson clover winter cover crop in 2001. Least squares means are not significantly different between the last sampling date in the cover crop and the first sampling date in cotton (one-tailed *t*-statistics, $P > 0.05$).

species and cotton and may have fed on the nectar produced by the flowers of the legumes and the extrafloral nectaries of hairy vetch. *Geocoris punctipes* does not require nectar for nymphal development and adult longevity when given abundant prey, although nectar helps them to survive in the absence of prey (De Lima and Leigh, 1984). Also, predation of heliothine eggs by *G. punctipes* is similar on cotton with or without extrafloral nectaries (Thead *et al*., 1985). Thus, provision of prey is likely to have played a more significant role than nectar provision in the success of the early-season habitat in enhancing this natural enemy in cotton. Apparently, a reduction in tillage conserved the habitat of red imported fire ants. *Geocoris punctipes* density in cotton generally was higher in crimson clover fields and on some occasions in the legume-mix fields compared to control fields, and fire ant density was higher in conservation-tilled fields compared to control fields. These results suggest that the early-season build-up of these natural enemies and conservation of within-field habitat translated into higher numbers of predators in cotton fields with cover crop/conservation tillage systems than in control cotton fields.

The number of heliothine eggs on cotton was similar across cover crop treatments over the growing season. Nevertheless, the need for insecticides to manage heliothine larvae was reduced by one to two applications in conservation-tilled fields with winter cover crops compared to control fields. These results indicated that the early-season build-up of natural enemies in the cover crops and conservation of habitat of natural enemies subsequently resulted in reduction in heliothine damage in conservation-tillage cotton with these cover crops compared to conventional-tillage cotton without cover crops (Box 19.1). Yields of seed cotton (i.e., cotton with lint and seed before cleaning) for cover crop/conservation-tilled fields were either higher, particularly for fields with a legume cover crop, or comparable to those for control fields. In summary, cover crops and conservation tillage promoted biological control of these pests in cotton and minimised the need for insecticides without reduction in yield. Detailed economic analyses were not done, but cost of insect control was reduced in cover crop/conservation-tilled fields without incurring economic loss through lower yields. Further benefits of this approach are the decrease in soil erosion, increase in soil organic matter, and a reduction in insecticide contamination of the environment.

In an earlier study, Bugg *et al*. (1991) determined that *G. punctipes* occurred in high densities on subterranean clover (*Trifolium subterraneum* L.), and there was evidence that the high densities observed amid dying mulches translated into greater predation of fall armyworm (*Spodoptera frugiperda* (J.E. Smith)) egg masses on cantaloupe foliage. Likewise, Ruberson *et al*. (1995) suggested that the high abundance of red imported fire ants in a crimson clover/strip-tilled field was responsible for the reduction in pest populations in this field relative to the conventionally tilled field without the cover crop.

According to the Conservation Technology Information Center's National Crop Residues Management Survey (2010), conservation tillage accounted for 41.5% of US planted crop area in 2008, compared with 26% in 1990. Widespread adoption of genetically engineered *Bt* germplasm has limited the usefulness of cover crops for managing heliothines in production of conventional cotton. However, this pest complex still ranked second in yield reduction for conventional cotton in the state in 2010 (Williams, 2011). Also, heliothines are major economic pests in organic cotton in Georgia (Tillman *et al*., 2008). Analysis of available data collected by an Organic Trade Association survey of US organic cotton producers determined that 4,343 ha of organic cotton were planted in the US in 2009, an increase of 26% over the previous year (OTA, 2010). Because the use of *Bt* cotton is prohibited in organic production of cotton (SAN, 2007), organic growers may benefit economically by using cover crops

Box 19.1 Benefits of a crimson cover crop in conservation-tillage cotton

Crimson clover provided a habitat for predator populations to build up in the spring and provided nectar for bees and other pollinators and parasitoids while increasing nitrogen in the soil, improving soil quality and reducing runoff and soil erosion.

Photo: K.J. Graham

Management of the cover crop strategically placed a strip of habitat in the cotton field so that the heliothine egg predator, G. punctipes, could relay from crimson clover to cotton.

Photo: H. Pilcher

The decreased need for insecticides to manage heliothine larvae in crimson clover cotton compared to control cotton indicated that the early-season build-up of predators in the cover crop and relay of predators from the cover crop onto cotton resulted in a reduction in heliothine larval damage to cotton.

Treatment	**No. times economic threshold for heliothine pests exceeded**
Control	**2.0a**
Crimson clover	**0.75b**

Means are not significantly different between cover crop treatments (one-tailed *t*-statistics, $P > 0.05$).

and conservation tillage practices, and new Global Positioning System (GPS) technology is available to help growers establish and maintain row patterns in cover crop fields. So, in Georgia, cover crops are beginning to be utilised in organic production of corn (*Zea mays* L.) and soybean (*Glycine max* L. Merr.), and research has been initiated to incorporate cover crops and conservation tillage in organic cotton and peanut (*Arachis hypogaea* L.) production (J. Tescher, personal communication, 2010).

CONSERVATION BIOLOGICAL CONTROL BY SYRPHID LARVAE OF *NASONOVIA RIBISNIGRI* AND OTHER APHIDS IN ORGANICALLY GROWN LETTUCE ON THE CENTRAL COAST OF CALIFORNIA

Almost 80% of the lettuce consumed in the USA is grown in California (NASS, 2010) where it is a billion-dollar industry (CDFA, 2008). In 2008, over 101,175 ha of lettuce were planted in California (NASS, 2010) with 8% grown using certified organic methods (ERS, 2008). Over 70% of the lettuce produced in California is grown in the Central Coast region, primarily in the highly productive Salinas Valley, which runs through the heart of Monterey County (Monterey County, 2009). Both leaf and head lettuce varieties are produced on the Central Coast and sold as whole heads in cartons, as trimmed hearts and in bagged salad mixes. Lettuce is planted in Monterey County from January to August, and it is harvested from April to December (Smith *et al.*, 2009).

A new pest

In 1998, *Nasonovia ribisnigri* (Mosley), a new invasive pest of lettuce, locally referred to as the lettuce aphid or red aphid, became established in the Salinas Valley (Chaney, 1999). Originating in Europe, *N. ribisnigri* has become established in Asia, the Middle East and North and South America (Blackman and Eastop, 2000). *Nasonovia ribisnigri* is greenish-orange to pink in colour and establishes dense colonies in the inner leaves of the lettuce head, making it unmarketable (Liu, 2004). Conventional growers have a range of insecticides available to suppress *N. ribisnigri* populations, including systemic insecticides such as neonicotinoids. Suppressing incipient *N. ribisnigri* infestations is crucial in conventional lettuce production because chemical control has limited efficacy once the infestation is protected by outer lettuce leaves, and the crop has outgrown the window of protection provided by at-plant neonicotinoid treatments. While specific thresholds have not been established, growers run the risk of having their lettuce crop rejected for sale if *N. ribisnigri* is detected at even very low levels.

From 1998 to 2001, management of *N. ribisnigri* was problematic for organic lettuce growers because attempts by these growers to suppress *N. ribisnigri* infestations using available insecticides, such as insecticidal soap, were ineffective (Colfer, 2004). Some, but not all, organic growers were planting strips of flowering plants, also known as insectary plants, in their lettuce fields to attract beneficial insects. During these initial years, growers and university personnel observed that, often in the absence of any pest management intervention, fields of organic lettuce that were infested with *N. ribisnigri* early in the season were largely aphid-free and marketable by the harvest date (Chaney and Smith, 2005). By 2001, University of California Farm Advisor William Chaney, Ramy Colfer of Mission Organics and other organic growers had concluded that aphidophagous syrphid larvae were playing a major role in the suppression of *N. ribisnigri* in organic lettuce fields on the Central Coast of California (Colfer, 2004). However, a small percentage of lettuce fields remained unmarketable at harvest time due to aphid infestation, leading growers and researchers to ask if there were ways to enhance the activity of syrphids and make aphid suppression in organic lettuce more predictable.

Syrphid flies belong to the family Syrphidae and are also referred to as hoverflies or flower flies. Many species of syrphids have predatory larvae that feed on aphids (Bugg *et al*., 2008). Adult syrphids are not predaceous. Both male and female syrphids require pollen for gametogenesis (Chambers, 1988). For energy, syrphid adults exploit floral nectar and in some cases honeydew, a sugar-rich material excreted by aphids and other Hemiptera.

Insectary plantings

Once the connection between syrphid larvae and *N. ribisnigri* suppression seemed clear, interest in evaluating the best species and density for insectary plantings intensified among organic growers and university researchers on the Central Coast (Chaney and Smith, 2005). Insectary crops are plants that provide resources such as nectar and pollen to predators and parasitoids. Growers incorporate insectary crops into fields with the aim of enhancing the pest-suppression activity of natural enemies (Landis *et al*., 2000). One of the first promoters of insectary plantings on organic farms in California was Robert 'Amigo' Cantisano (UCSC, 2010). Cantisano recalls that before the national demand for organic produce rose in the 1990s and product quality standards increased, there was limited interest in insectary plantings among the Central Coast's traditional organic vegetable growers (R. Cantisano, personal communication, 2010). According to Cantisano, the arrival of *N. ribisnigri* in the Salinas Valley 'changed everyone's attitude' towards the importance of insectary plantings (R. Cantisano, personal communication, 2010).

Among the many insectary plants that have been evaluated on California's Central Coast, sweet alyssum (*Lobularia maritima* L. (Desv.)) has proven to be among the most attractive to syrphid adults and the easiest to incorporate into field production (Chaney, 1998; Colfer, 2004; Chaney *et al*., 2006; Bugg *et al*., 2008). Damage by flea beetles to alyssum has led some Central Coast organic growers to incorporate phacelia (*Phacelia tanacetifolia* Bentham) and buckwheat (*Fagopyrum esculentum* M.) in their insectary plantings (Ramy Colfer, personal communication). Dhani-ya coriander (*Coriandrum sativum* L.), a cultivar of coriander which flowers quickly, is also highly prized by organic growers on the Central Coast for the apparent abundance and diversity of syrphid adults that it attracts. Some growers use 'good bug blends' – mixtures that include clovers, herbaceous plants and grasses – as insectary crops in their organic lettuce production in the Salinas Valley.

Both the ratio of insectary crop to lettuce and the insectary intercropping pattern vary among organic farms. Organic growers on the Central Coast dedicate up to 9% of lettuce fields to insectary plantings, with 5% considered the norm (Tourte *et al*., 2009). Chaney (1998) demonstrated that densities of beneficial insects were higher and aphids were lower within an

11 m range of insectary strips planted in lettuce than at greater distances from insectary strips. He recommended one insectary strip roughly every 33 m. Colfer (2004) documented a threefold increase in syrphid oviposition on romaine lettuce adjacent to (0.6–3 m) alyssum versus romaine 16 m from alyssum. However, the concentration of syrphid eggs primarily near insectary plantings is brief, for syrphid eggs and larvae soon become distributed across lettuce fields (Colfer, 2004).

It is important to keep in mind that syrphid adults are strong fliers and that syrphid oviposition is stimulated by the presence of or proximity to aphids and compounds associated with them, regardless of immediate availability of floral resources (Chandler, 1968a; 1968b; Shonouda *et al.*, 1998; Verheggen *et al.*, 2008). The Salinas Valley is characterised by organic farms, roadsides, rangeland and riparian habitat that harbours abundant natural flowering vegetation. Depending on the specific agricultural landscape in which a field is located, naturally occurring floral resources may contribute as much as planted insectaries to the suppression of *N. ribisnigri* by syrphids. Some organic growers have benefited from the activity of syrphids without intercropping insectary plants in their lettuce fields, presumably because the floral resources near the lettuce field are sufficient to enhance syrphid activity.

The syrphid 'team'

Fourteen species of aphidophagous syrphids have been reared from commercial organic romaine fields in and around the Salinas Valley (Smith and Chaney, 2007; Smith *et al.*, 2008). Four species predominate: *Toxomerus marginatus* (Say), *Platycheirus stegnus* (Say), *Sphaerophoria sulfuripes* (Thomson) and *Allograpta obliqua* (Say). *Toxomerus marginatus* and *S. sulfuripes* comprised 39% and 13%, respectively, of over 1,000 syrphids reared from several farms during an intensive seven-month survey in 2005 (Smith and Chaney, 2007). While these two species were recovered from moderately and highly infested romaine lettuce fields, it is noteworthy that their eggs and larvae were also recovered in significant numbers from romaine fields in which aphid densities were too low to be of concern to the grower. For example, *T. marginatus* and *S. sulfuripes* were collected from a variety of romaine that is highly resistant to *N. ribisnigri* but which supports low populations of the potato aphid, *Macrosiphum euphorbiae* (Thomas). From a biological control perspective, it is significant that there are species in the syrphid complex that are present in fields where aphid populations are at sub-economic levels. By contrast, *P. stegnus*, which comprised 27% of the syrphids reared in 2005, was collected primarily from highly infested fields. While other syrphid species collected from organic romaine lay eggs singly or in groups of two or three, *P. stegnus* oviposits clusters of parallel, contiguous eggs. It was not uncommon to encounter clusters of five to seven eggs, and a single cluster of 18 eggs was recovered. This egg-laying behaviour suggests that *P. stegnus* is adapted to take advantage of plants with high aphid densities.

Weekly whole-plant samples from multiple organic romaine farms in 2005 and 2006 revealed that peak densities of five to nine syrphid larvae per romaine head one to two weeks before harvest are not uncommon (Smith and Chaney, 2007; Smith *et al.*, 2008). These peak syrphid densities consistently coincided with the crashing of aphid populations in the romaine field. Replicated field trials were carried out in 2007 to determine the effect on aphid populations of experimentally removing syrphid larvae (Smith *et al.*, 2008). The organically approved formulation of spinosad (Entrust®) was applied once a week for five weeks prior to harvest in 7.6 m plots of romaine to suppress syrphid larvae. Spinosad is an effective insecticide for suppressing certain dipterous larvae, and pilot studies had determined that it suppresses syrphid larvae without affecting aphid populations (W.E. Chaney, personal communication). Where Entrust was applied, syrphid larval populations were suppressed, and romaine was unmarketable at harvest because of aphid infestation (Smith *et al.*, 2008). In plots where Entrust was applied, the highest average whole plant syrphid larva density was 2.84 ± 0.58 (SEM). In untreated romaine, the highest average whole plant densities of syrphid larvae ranged from 2.75 ± 0.58 to 9.08 ± 0.58, depending on the site (Smith *et al.* 2008). In untreated plots, where syrphids were allowed to persist, romaine was marketable at harvest (Figure 19.3).

Other natural enemies

Parasitic wasps are not considered important in the suppression of *N. ribisnigri* because the pest colonises the interior of the lettuce head, where it is largely protected from these natural enemies. Infections by the entomogenous fungus *Pandora* spp. commonly sup-

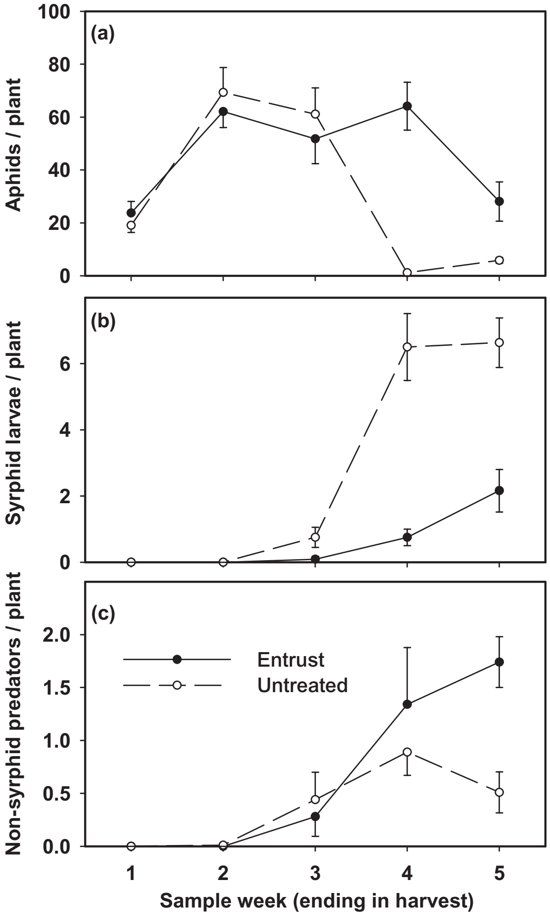

Figure 19.3 The effect of suppressing syrphid larvae with Entrust, an organically approved insecticide, in an organic romaine field in Hollister, California. The graphs illustrate three key aspects of aphid suppression by syrphids: 1) When syrphids are suppressed, lettuce is unmarketable because of aphid infestation a), 2) Syrphids can reach peak densities of ~6 larvae or more per romaine head before harvest b) and 3) Non-syrphid predator densities overall are very low c). Data represent average insect densities per plant (±SEM) (from: Smith *et al.*, 2008).

press *N. ribisnigri* and other aphids in lettuce during the early months of production, which overlap with the final winter rains in the Salinas Valley (S. Koike, personal communication, 2010).

Other predators found in organic romaine in the Salinas Valley include ladybird beetles (Coccinellidae), dwarf spiders (Linyphiidae: Araneae), big-eyed bugs (*Geocoris* spp.: Lygaeidae), minute pirate bugs (*Orius* spp.: Anthocoridae), green lacewings (*Chrysopa* and *Chrysoperla* spp.: Chrysopidae), brown lacewings (*Hemerobius* spp.: Hemerobiidae), rove beetles (Staphylinidae) and predatory thrips (Thysanoptera) (Smith and Chaney, 2007; Smith *et al.*, 2008). Between 61% and 97% of romaine plants collected from five organic farms in 2005 contained either syrphid eggs or larvae; the range for plants containing non-syrphid predators was 16–60%, depending on the field (Smith and Chaney, 2007). Syrphid larvae comprised between 85% and 96% of all predators collected from whole-plant samples at most research sites in 2006 (Smith *et al.*, 2008). Non-syrphid predators were consistently found at much lower densities than syrphid larvae. Except for dwarf spiders, no other predators besides syrphids were found in every field.

Organic romaine growers dedicate on average 5% of crop area to insectary plantings to ensure the marketability of the remaining 95% of the crop; the cost of alyssum seed is roughly US$10.00/ha (Tourte *et al.*, 2009). Organic leaf lettuce growers who apply insecticides to manage caterpillars and aphids spend on average an additional $290/ha on pest management. The estimate for pest management in conventionally grown romaine hearts is $1100/ha (Smith *et al.*, 2009). In recent years, the Dutch plant breeding company Rijks Zwaan has produced varieties of lettuce that are highly resistant to *N. ribisnigri* (van Helden *et al.*, 1995). These varieties have enabled some organic lettuce growers to reduce the area that they dedicate to insectary plantings (Phil Foster, personal communication, 2010). However a biotype of *N. ribisnigri* that is able to survive on resistant lettuce varieties has already been identified in Europe (Rijks Zwaan, 2010).

Summary

Within the diverse species complex of syrphids suppressing aphids in the Salinas Valley, the predominant species apparently complement each other by exploiting distinct predatory guilds. *Toxomerus marginatus* and *S. sulfuripes* will oviposit in fields that have very low numbers of aphids as well as in more infested fields, while there is evidence that *P. stegnus* is specifically adapted to colonise fields with high aphid populations (Smith and Chaney, 2007). At least 11 additional syrphid species contribute to aphid suppression. Syrphid larvae operate with a high degree of efficiency in the inner leaves of the lettuce head where other natural enemies are apparently less effective. Among predators in organic lettuce, only syrphid larvae reach high densities in the crucial weeks immediately before harvest. When these larvae are killed, the crop is unmarketable because of aphid infestation (Smith *et al*., 2008). The suppression of *N. ribisnigri* by naturally occurring syrphid species on California's Central Coast is a noteworthy example of an invasive pest of a high-value fresh market crop being effectively managed by endemic natural enemies (Box 19.2). This is a contemporary example of the effectiveness of 'new associations' in biological control (Hokkanen and Pimentel, 1989). The break-even costs for California's organic lettuce growers depend on market price and yield per hectare, which can vary considerably from year to year (Tourte *et al*., 2009). Therefore it is difficult to put a dollar value on syrphid predation. However, it seems unlikely that California's organic growers could supply the bulk of the nation's demand for organic lettuce without the aphid suppression services provided by syrphid flies.

BEETLE BANKS

Background

In the European Union (EU) 30% of the farmed landscape is devoted to the production of cereal crops for human consumption and animal feed. Of this, winter

Box 19.2 Conservation biological control of the lettuce aphid in organic lettuce

Syrphid larvae (top right) feed on the lettuce aphid and other aphids. Organic growers enhance the activity of these natural enemies by providing floral resources (nectar and pollen) to adult syrphids (bottom right) in lettuce fields with in-field plantings of alyssum (below) and other insectary plants.

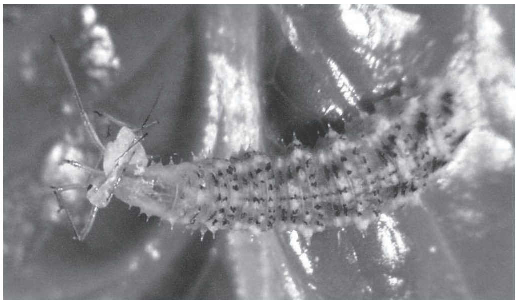

Photo: W.E. Chaney

Photo: W.E. Chaney

Photo: H.A. Smith

wheat (sown in autumn) accounts for 46% of cereal production. The main insect pests are cereal aphids, some of which invade the crop in the autumn, and because they transmit damaging viruses (e.g. barley/cereal yellow dwarf viruses), most crops are prophylactically treated with insecticides unless they are late-sown, which reduces the chance of aphid infestation. Aphids also invade crops in the summer, causing yield loss (Mann *et al.*, 1991), whilst the honeydew encourages sooty moulds near harvest (Poehling *et al.*, 2007). In Western and Central Europe, *Sitobion avenae* F. (grain aphid), *Metopolophium dirhodum* (Walker) (rose-grain aphid) and *Rhopalosiphum padi* L. (bird cherry-oat aphid) are the predominant pest species, but *Schizaphis gramminum* (Rondani) (greenbug) and *Diuraphis noxia* (Kurdjumov) (Russian wheat aphid) which are more typical of warmer climates, are spreading as Northern Europe experiences warmer winters (Poehling *et al.*, 2007).

The development of beetle banks

A programme of research was initiated in the 1980s in the UK by S. Wratten at Southampton University and the Game Conservancy Trust (now Game and Wildlife Conservation Trust) aimed at developing an IPM system for cereal crops. Exclusion studies had identified that generalist predators, mainly carabid and staphylinid beetles, were capable of contributing to cereal aphid control (Edwards *et al.*, 1979; Chiverton, 1986), especially early in the spring when predator:prey ratios were high and before aphidophagous species were available in sufficient numbers. Earlier work had identified that tussock-forming grasses (e.g. *Dactylis glomerata* L. and *Holcus lanatus* L.) provided appropriate and relatively stable conditions during the winter (Luff, 1966) and resulted in greater survival compared to other plants (D'Hulster and Desender, 1982). Such habitats typically occurred between field margins and hedgerows, and these were found to support high densities of overwintering generalist predators (Sotherton, 1984; 1985). These predators subsequently colonised the adjacent field in spring, but in large fields species which dispersed by walking took until June to reach field centres (Coombes and Sotherton, 1986). Unfortunately, between the 1950s and 1970s many hedgerows in the UK were removed, purportedly to increase agricultural productivity and efficiency. Many remaining hedgerows have become degraded, including the hedgebase where herbicide and fertiliser drift destroys the complex plant community (Bealey *et al.*, 2009). The creation of 'island habitats' across fields was devised as a way to replace these losses with a simple-to-manage habitat that would provide overwintering cover and encourage a more extensive and earlier coverage of the field with generalist predators (Thomas *et al.*, 1991).

Evaluating effectiveness

Initial studies confirmed that the banks were quickly colonised by very high densities (up to 1,500 per m^2) of overwintering beetles (Thomas *et al.*, 1992), which led to their being called 'beetle banks' (Box 19.3). The mean density (585 per m^2) across a number of later studies was lower (Table 19.1), and in these studies, densities were maintained for up to 10 years and were comparable to or even higher than those of field margins (Thomas, 2001; Collins *et al.*, 2003; Macleod *et al.*, 2004). Considerable variation was found between years and study sites and was attributed to the many different variables (e.g. soil type and landscape composition) and anthropogenic impacts (e.g. crop management practices) occurring in adjacent fields. Overall, the invertebrates found within the banks comprised Carabidae, Staphylinidae (mostly *Tachyporus* spp.) and Araneae (mostly Linyphiidae).

The effectiveness of beetle banks may be estimated by calculating to what extent they are likely to increase the number of predatory natural enemies within the adjacent field. If beetle banks are expected to enhance predators to 75 m on either side (this being the recommendation given above) and support on average 585 predators per m^2 or 2,180 per m^2 at the highest estimate (Collins *et al.*, 2003), then this would raise the number of predators by 3.9 per m^2 or 14.5 per m^2 respectively, assuming all emigrate from the beetle bank during the summer. Actual predator densities within a cereal field without a beetle bank varied between 29.3 per m^2 on 3 June declining to 11 per m^2 by 13 July (Holland *et al.*, 2004). Thus, depending on predator densities within the beetle banks and fields (i.e., predators not originating from the beetle bank), beetle banks can supplement existing predator densities by over 50% (Figure 19.4).

Two studies examined whether the beetle banks led to more even predation across fields. Predation of artificial prey still occurred at the maximum distance used

Box 19.3 How to create beetle banks

The banks are created by ploughing two furrows together to create a raised bank 40 cm high and approximately 2 m wide. The ends of the beetle bank remained separated from the field margin by a spray boom width to minimise the disruption to agricultural operations.

To create optimal overwintering conditions for beetles the banks are best sown with tussock-forming grass species. A range of different grass species and mixtures were compared to see if this affected colonisation rates, but the most aggressive grass*, Dactylis glomerata* (Cock's Foot), quickly dominated although it does provide appropriate conditions (Thomas *et al*., 1991; Collins *et al*., 2003) and consequently most farmers only sowed this species (Thomas, 2000).

Photo: J.M. Holland

Photo: J.M. Holland

These grasses were found to maintain their structure for at least a decade and flowering plants also started to colonise the strips (Thomas *et al*., 2001). Based upon the distance that beetles were dispersing from the banks, it was advised that fields larger than 15 ha should be divided by multiple beetle banks spaced no further than 150 m apart (Thomas *et al*., 1991).

Photo: P. Thompson

Table 19.1 Densities of predatory natural enemies within beetle banks in three studies.

Reference	**Year**	**Carabidae**	**Densities (per m^2)**		
			Staphylinidae	**Araneae**	**Total predators**
Macleod *et al*., 2004	1987	11	1	6	17.9
	1988	111	44	22	177.1
	1989	20	39	26	85.3
	1990	14	28	43	84.6
	1991	53	84	48	185.2
	1992	72	125	45	242.6
	1993	45	91	25	160.9
Collins *et al*., 2003	1994	80	377	136	593
	1995	301	857	89	1247
	1996	423	1550	207	2180
	1997	79	351	84	514
Thomas, 2001	1997	200	340	380	920
	1998	250	480	470	1200
	Mean				585.2

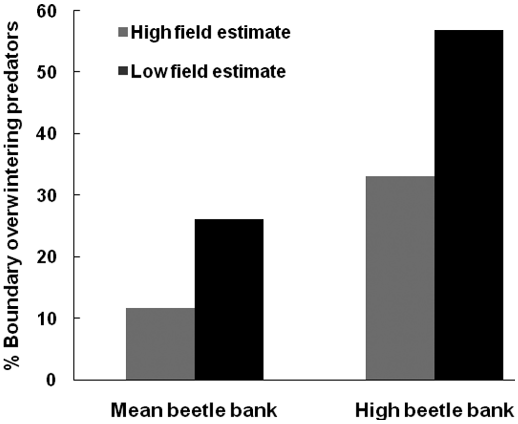

Figure 19.4 Proportion of predators originating from beetle banks for low and high estimates of predator densities within fields (see text for details).

(60 m), although predation was highest on the bank itself (Thomas, 1990). The impact on naturally occurring aphid infestations of excluding ground-dispersing predators was evaluated within enclosed plots established at 8, 33, 58 and 83 m from a beetle bank (Collins *et al*., 2002). The mean number of aphids and aphid peak populations were reduced up to 58 m, but reductions were greatest at 8 m. The generalist predators probably had a lower than anticipated impact because the aphids invaded the crop relatively late in the season and increased rapidly, outstripping their control as found in other exclusion studies (Holland *et al*., 1996).

The distribution of generalist predators may be affected by the presence of a beetle bank. A brief wave of emigration of generalist predators from the banks was detected in April or May (Thomas *et al*., 1991; 2000; Collins *et al*., 2002) followed by a period in which there was an even spread of boundary-overwintering predators across the adjacent field (Thomas *et al*., 2000). More recent studies of insect spatial distribution within fields surrounded by hedgerows found that numbers of boundary-overwintering species were highest within 60 m of the boundary (Holland *et al*., 2009) with a peak in their numbers during May, followed by a decline during June, also found by Thomas *et al*. (2000). This explains why in a small field (2.2 ha) the more mobile boundary-overwintering predators (e.g. *Tachyporus* spp. and linyphiid spiders) showed no association with margins (Holland *et al*., 1999). The impact of beetle banks may be reduced if predators remain within them all year round. The density of Carabidae decreased by two-thirds between winter and spring with a slight increase in summer compared to spring (Thomas, 2001). Between winter and spring, Staphylinidae densities declined by three-quarters and Araneae densities declined by a half, indicating a similar emigration. Some losses may be ascribed to overwinter mortality rather than emigration.

Uptake of beetle banks

Despite widespread promotion of the concept since the early 1990s by the Game Conservancy Trust and Game and Wildlife Trust, uptake in the UK is poor, even after the approach was supported under English agri-environment schemes (AES). In the Countryside Stewardship scheme and its successor, the Environmental Stewardship (ES) scheme, payments were the equivalent of approximately £12 per 100 m length per year. The Entry Level Scheme which forms the first tier of ES has been adopted by 70% of farms in England, but only 1.4% had established beetle banks by 2009 (Boatman *et al.*, 2007). In an earlier farmer survey it was highlighted that more information on the biocontrol potential of beetle banks was needed, and this may partly explain the poor uptake (Thomas, 2000). Other likely reasons are that the threat from cereal aphids is diminishing and insecticides are relatively cheap and can easily be added to the fungicide spray programme. In most cases, the farmers were establishing beetle banks for their wider biodiversity benefits, for game management, or to demarcate areas to aid farming operations. The banks support other invertebrate taxa including grasshoppers, some butterflies and invertebrates important as food for bird chicks, and thus they are used as nesting habitat, especially by grey partridge *Perdix perdix* L. (Thomas *et al.*, 2001) and harvest mice (*Micromys minutus* Pallas).

The beetle bank concept has also been tested across the world, for example in Denmark (Reidel, 1992), Sweden (Chiverton, 1989), Finland (Helenius, 1995), the USA (Carmona and Landis, 1999) and New Zealand (Berry, 1997), but in many countries grassy perennial field margins provide a similar function and are the commonest way of dividing fields, although a raised bank does give some extra benefit on heavier soils by creating drier conditions (Sotherton, 1985). In the UK, grass margins (buffer zones) have been widely established (73,000 ha by 2009) using ES funding, and these may likewise support overwintering generalist predators and supply alternative prey in the summer for a range of predators and parasitoids (Meek *et al.*, 2002). Landscape-scale evaluations confirmed that aphid control was related to the proportion of area occupied by grass margins (Holland *et al.*, 2008a). However, exclusion studies that isolated the impact of ground and flying predators revealed that more than 90% control was achieved by flying predators compared to a maximum of 40% by ground-based predators alone (Holland *et al.*, 2008a). This level of control was only achieved when fields were surrounded by 6 m-wide grass margins, and control occurred more slowly (Holland *et al.*, 2008b). These studies were, however, conducted in June and July when populations of boundary-overwintering predators were declining. This decline may be due to natural mortality and predators retreating back to the margins, although summer sampling indicated this was not occurring (Thomas, 2001). Alternatively, the high level of control may be the consequence of predation by the larger field-overwintering species (e.g. the carabids, *Pterostichus* spp.). These species increased rapidly from early June and far outweighed those originating from the boundaries (Holland *et al.*, 2009).

Economics

The economic benefits of beetle banks have been estimated based only upon the cost of establishment and income foregone for the land occupied by the bank rather than any measure of reductions in insecticide use or yield gain. In 2002, the establishment costs were £975 per ha with subsequent costs of £2 per ha for income foregone from the land occupied (Collins *et al.*, 2002). Thus the agri-environment scheme payments of £600 per ha would cover these costs within two years and be more profitable in following years. The cost of an insecticide was between £3 and £12 per ha without application costs, but aphicides are typically added to a fungicide programme. Therefore, beetle banks are not economically feasible without the AES payments based upon savings in insecticide costs alone. However, there are other benefits such as enhancing natural enemy populations that may operate farm-wide, and the enhancement of wildlife.

Summary

It is unlikely that beetle banks will ever be widely used in cereal crops whilst cheap and efficient insecticides remain available, but for organic producers and those producing horticultural crops in Europe where the range of insecticides is dwindling owing to revisions to pesticide legislation (Council directive 91/414/EEC) then they may contribute to an IPM programme. Other habitats that are already present on farmland, such as grassy strips between fields or associated with fence lines, ditch edges, shelterbelts and the base of hedgerows, can support high densities of overwintering generalist predators (Griffiths *et al.*, 2008). These areas may also be suitable for breeding, aestivation and foraging, providing a source of alternative prey for periods when pests are insufficient. Such habitats may also be supplemented with flowers and hedgerows as these can provide a source of pollen and nectar for their natural enemies such as hoverflies (Cowgill *et al.*, 1993; Hickman and Wratten, 1996), parasitoids (Berndt *et al.*, 2006; Vollhardt *et al.*, 2010), lacewings (Robinson *et al.*, 2008) and predatory Heteroptera (Coll, 1998), whilst also diversifying the range of habitats for natural enemies. Floral resources can boost parasitoid movement, longevity and fecundity (Berndt and Wratten, 2005); however, flower species must be carefully chosen so that they are exploited primarily by the natural enemies rather than the pests (Baggen *et al.*, 1999; Lavandero *et al.*, 2006; Winkler *et al.*, 2009) and that natural enemy parasitism is not enhanced (Jonsson *et al.*, 2009). Combining the two habitats is not recommended because the tussock-forming grasses usually outcompete the flowering species. However, providing both habitats within fields may create synergistic advantages. Such farm and landscape diversification can enhance natural enemy activity (Bianchi *et al.*, 2006). Diversifying the type and number of predator guilds such as ground- and crop-active, day- and night-active, at the farm and landscape scale may also improve the robustness of biological control (Weibull *et al.*, 2003).

CONCLUSIONS

Many variables determine whether biodiversity-based habitat manipulation approaches can be successfully implemented in agroecosystems, including the value of the crop, the nature of the pest damage and the susceptibility of key pests to suppression by natural enemies. The three case studies outlined in this chapter illustrate both the broad applicability of habitat manipulation to enhance biological control, and the challenges to implementing it. We have demonstrated how the ecological services of beneficial arthropods can be integrated into pest management programmes for basic grains, fresh produce and fibre crops in temperate, Mediterranean and subtropical growing environments. Habitat manipulation schemes for provisioning habitat, floral resources, and prey to natural enemies of targeted pests must be designed according to the specific needs of the natural enemy complex in time and space. Habitat manipulation must also fit easily into the grower's way of doing things, and growers will not be persuaded to take up these conservation biocontrol technologies without evidence that they reduce the incidence of pests and are cost effective. Demonstrating that habitats incorporated into agricultural systems for enhancing natural enemies have additional benefits beyond biocontrol can improve their uptake as they may appeal to a grower's interests or philosophy. For example, beetle banks can be adopted to also improve nesting and feeding habitats for game birds. The additional environmental benefits created by the adoption of conservation biocontrol such as reduced use of pesticides and therefore a reduction in off-farm pollution or encouragement of biodiversity, may create financial savings elsewhere (e.g. reduced costs of removing pesticides from drinking water), which should be recognised, and some of this could be returned to the farmers through incentive schemes. Even where financial support is available, farmers may still not adopt conservation biocontrol when insecticides remain effective and cheap. Growers may seek alternative technologies only when faced with pest resistance (e.g. as has occurred in protected cops), pressure from retailers (e.g. crop assurance schemes) or statutory restrictions (e.g. Denmark, organic certification). Nevertheless, each of the examples described in this chapter shows how growers and researchers have worked together to gather practical information on biodiversity-based approaches to suppress insect pests by providing habitat, resources, and biological diversity. As restrictions on insecticide use increase in North America, Europe and other parts of the world, these models of collaboration between growers and researchers to suppress pests while reducing insecticide use may become more common.

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