K·STATE
Research and Extension

Biological Control of Agricultural Pests in Kansas

Biological Control

Biological control is the reduction of pest populations by the actions of other living organisms, often collectively referred to as natural enemies or beneficial species. Virtually all organisms categorized as agricultural pests have natural enemies, although they cannot be relied upon to suppress pest populations in all situations. Nevertheless, it is important that farmers recognize, manage, and conserve natural enemies that normally help maintain pest populations below economically damaging levels. These beneficial species reduce crop losses and the need for costly control measures that may have undesirable side effects on human health and the environment. A key to understanding integrated pest management (IPM) is the concept of economic threshold — the critical density of pests beyond which the cost of controlling them is economically justified. In fact, many herbivorous arthropods inhabit field crops but do not become pests (cause economically significant crop losses) unless their natural enemies are disrupted by pesticides or other cultural activities.

The biological control of pests in field crops is best considered within the larger context of agronomic practices, many of which have powerful effects on the arthropod community. Because pests, and their natural enemies, move among crops seasonally, and in some cases migrate over long distances, producers must consider patterns of insect movement over landscape scales. Even though sometimes insufficient, biological control should be the foundation of all the IPM programs developed to protect field crops. A good IPM program is a sustainable combination of pest control tactics that functions to reliably maintain pest populations below economic levels in a cost-effective manner. Cultural practices that generally integrate well with biological control include cultural controls (e.g., no-till, cover crops, planting date selection, etc.), crop rotation, and selection of pest-resistant cultivars. When a pesticide application is justified, biological control agents can be conserved by opting for insecticides with selective modes of action (e.g., insecticides that must be consumed, as opposed to contact nerve toxins), spot treatments that restrict pesticide applications to heavily infested areas and leave untreated refuges for natural enemies, and the use of biopesticides, formulations of fungal or viral diseases specific to targeted pests.

To take full advantage of biological control, and understand its limitations, producers must develop a good understanding of the biology of the pest and its natural enemies, and learn to identify various life stages of relevant insects in the field. Field scouting is usually necessary to monitor the activities of natural enemies, evaluate their impact on pest populations, and anticipate the need for additional control measures. Although three distinct types of biological control are recognized (conservation, importation, and augmentation), conservation biological control, by far, provides the most important benefits for field crop producers in Kansas.

Conservation Biological Control

Conservation of natural enemies is a straightforward concept that can quickly become complex in practice. At the most basic level, conservation biological control means avoiding cultural practices that harm natural enemies and implementing practices that attract, encourage, or benefit them. The challenge is to understand exactly what cultural practices are harmful to natural enemies and why, and how to integrate more beneficial alternatives into production systems in a cost-effective and convenient manner. This requires not only a good understanding of the biology and ecology of key natural enemies, but also a willingness to modify production practices to accommodate their needs. Many natural enemies do not feed only on pests, but may also prey on various non-pest insects, other beneficial arthropods (intraguild predation), and even other individuals of their own species (cannibalism). These behaviors are not necessarily detrimental to biological control, as they facilitate natural enemy survival when prey are scarce. Natural biological control often occurs unnoticed in healthy agroecosystems, simply because natural enemies consistently maintain a wide range of potential pests at low densities. In fact, many pest outbreaks can be linked to a disruption of normal biological control processes.

The most obviously harmful practice for conservation biological control is the use of non-selective insecticides (also called broad-spectrum insecticides) that kill natural enemies along with target pests. In general, these pesticides tend to be older, generic materials with expired patents such as synthetic pyrethroids and organophosphates that act as contact nerve toxins. Although many pests now express variable levels of resistance to these products, they are often selected because they are the cheapest alternative. Insecticides can have a wide range of adverse effects on natural enemies, killing them directly, impairing their foraging and reproductive abilities, and depriving them of food. Nevertheless, there are many ways that insecticides can be successfully integrated into a production system while minimizing their negative effects on beneficial species.

Various proteins derived from the bacterium *Bacillus thuringiensis* (*Bt*) are selectively toxic to specific families of insects and are harmless to most natural enemies. These toxins must be consumed by the insect and activated by alkaline conditions in the gut, a characteristic of caterpillars, mosquito larvae, and other herbivorous insects. Unfortunately, most *Bt* formulations for foliar application lack residual efficacy under field conditions, as the toxins are subject to photo-oxidation in direct sunlight, and rainfall will wash them off the plants. Genetically engineered in-plant expression of *Bt* toxins (sometimes referred to as plant incorporated protectants) provides a solution to these problems, and has revolutionized the management of moth pests in corn and cotton, while demonstrating good compatibility with biological control. Many different *Bt* events have been incorporated into different crops. Although not all have been as effective as the original event targeting European corn borer, *Bt* crops have largely benefited conservation biological control by reducing the need for insecticide applications against various stalk-boring, defoliating, and root-feeding pests.

Insecticides with active ingredients such as spinosad and indoxacarb achieve selectivity through low contact toxicity and must be consumed by the insect to be activated. Since natural enemies typically do not consume foliage with the chemical on it, they are generally spared direct mortality, although they may still be exposed via consumption of contaminated prey. However, certain natural enemies, including many predatory bugs, are omnivorous, and also feed selectively on plant parts. Most adult predators and parasitoids also use floral resources (pollen and nectar), and pesticides with systemic activity can contaminate these resources, with negative effects on biological control agents and valuable pollinator species. In general, crops in bloom should never be sprayed, although commercial sunflowers are an exception, as they are particularly vulnerable to flower-infesting insects.

Even insecticides with contact toxicity can be applied in ways that minimize their effects on beneficial species. Damaging pest populations are often confined to portions of a field, rather than distributed evenly throughout it. Restricting treatment to affected areas will leave untreated areas to serve as reservoirs for natural enemies, in addition to reducing application costs. No insecticide application will be 100% effective. Surviving natural enemies are often key to finishing the job, recolonizing treated areas following degradation of the insecticide, accelerating the restoration of biological control, and often averting the need for subsequent applications. When biological control is disrupted by insecticide applications, formerly insignificant herbivores can become major pests (secondary pest resurgence), and a farm can develop dependency on chemical control measures once natural enemies have been eliminated (the pesticide treadmill effect).

Farmers should be conscious of cultural practices that can be detrimental to natural enemies. Plowing, cultivation, mowing, or harvesting operations can be disruptive to biological control if they coincide with critical life stages of natural enemies. The adoption of no-till and minimum-tillage agriculture has favored some beneficial arthropods (e.g., ground beetles, spiders, and other generalist predators that rely on crop residues for physical shelter). However, no-till agriculture can also benefit pests that use crop residues for shelter or pupate more successfully in undisturbed soil (e.g., false wireworms). Cultivation operations carried out during dry weather, or dust raised by traffic along dirt roads, can impede the foraging activities of small arthropods such as predatory mites, leading to outbreaks of their prey (spider mites) on corn or soybeans. The burning of crop residues can kill large numbers of beneficial insects, as can poorly timed flood irrigation. Marginal areas and non-crop habitats can serve as important reservoirs of many natural enemy species, facilitating their colonization of adjacent fields when pest populations develop. Excessive herbicide applications on marginal lands, pastures and fallow fields can negatively impact both plant and insect diversity, reducing the numbers of beneficial species locally available to colonize crops.

One of the biggest hurdles for sustainable biological control in field crops is the low diversity of plants and insects associated with large scale monocultures, which tends to favor pests over their natural enemies. Conservation of natural enemies is generally improved by encouraging plant and insect diversity in non-cultivated areas and wherever else this may be feasible. Strip-harvesting of alfalfa, where alternating strips of alfalfa are left uncut until the cut strips begin to regrow, is an excellent example of conservation biological control because it provides a continuous refuge and food supply for beneficial insects. Encouraging the growth of native perennial flowering plants on marginal lands will provide season-long resources for natural enemies (and pollinators), while simultaneously reducing the ability of annual weed species to propagate in these areas.

Despite the prevalence of monocultures, Kansas field crops benefit from very good levels of natural biological control pest control overall. A wide array of potential pests rarely exceed economic thresholds due to the activities of many resident beneficial species (described below). Most of these natural enemies are adapted to overwinter in Kansas and move across the agricultural landscape, colonizing various annual crops in sequence as prey such as aphids and caterpillars become available. Winter wheat is important in this regard, as it is the first crop to green up in spring, and it is very tolerant of defoliation up until the critical stage when the first hollow stem is produced. Most natural enemies that overwinter in Kansas complete their first generation on wheat in the spring, increasing their numbers a hundredfold or more before moving out into summer crops where they contribute to biological control of many other pests. It is therefore critical for farmers to avoid or minimize insecticide applications on wheat to ensure the production of sufficient natural enemies to provide adequate biological control of pests in summer crops.

The prophylactic treatment of seed with neonicotinoid insecticides is currently the most serious threat to sustainable biological control in Kansas field crops. Initially, seed treatment was promoted as a preferable and less costly alternative to broadcast applications of larger amounts of insecticide after pests reached economic levels. Unfortunately, the prophylactic application of an insecticide, in any amount, runs counter to the most basic principle of IPM: do not use any insecticide in a preventative manner or without economic justification. Although seed treatment can be justified, for example when populations of seed-destroying insects are established in a particular field, serious ecological problems develop when virtually all seed — of all crops — is treated and planted over vast acreages of farmland. Only a small fraction of the active ingredient is taken up by the crop plant, while the remainder leaches into the soil where it is highly mobile in ground water. This means the pesticide can be taken up by noncrop plants, contaminating nectar and pollen that are important supplementary foods for predators and parasitoids, as well as pollinators. Active ingredients such as thiamethoxam and imidacloprid, and many of their breakdown products, are also toxic to many nontarget organisms, including invertebrates responsible for decomposition and nutrient recycling in the soil and in freshwater ecosystems. These chemicals have been implicated in the precipitous global decline in abundance of overall insect biomass, threatening overall biodiversity and ecological stability by reducing the food supply for birds, fish, and all higher organisms. Effective biological control requires that natural enemies be able to sustain their populations within crop fields. This means that subeconomic populations of pests in crop fields are not merely tolerable, they are *essential* as a food supply for beneficial species. Some pests are necessary early in the crop cycle to attract natural enemies into the field and ensure pest populations do not escape control in later stages of crop development when economic damage is much more likely. Furthermore, regional economic analyses do not find any consistent economic benefits from the use of neonicotinoid seed treatments in Kansas. Seeds treatments, as currently used, pose a serious hazard to natural area-wide biological control in the agricultural landscape, apart from their broader environmental impacts.

Importation (Classical) Biological Control

High volumes of international trade and airline traffic have increased the frequency of exotic pests invading from other regions of the world. Exotic pests also can arrive unaided by humans, as when aphid species are transported across the Atlantic Ocean by hurricanes. When immigrant pests establish a foothold in a new geographic location, they can rapidly increase their populations and cause serious economic losses, simply because the co-adapted natural enemies that control them in their region of origin are absent. The local community of natural enemies may not respond to them immediately as prey, may lack adaptations necessary to exploit them, or may not be present in the crop at the right time to exert sufficient control, although many species may evolve the required adaptations over time. Examples of serious pests in Kansas of foreign origin include the Hessian fly, the European corn borer, the Russian wheat aphid, the alfalfa weevil, and more recently, the sorghum aphid.

The importation and release of natural enemies from a pest's country of origin is often called classical biological control. This approach gained impetus early in the 20th century following several dramatic successes, notably the importation of the vedalia beetle to control the cottony cushion scale that was threatening the nascent California citrus industry. Importation biological control of weeds has had many dramatic successes, especially against aquatic weeds, usually by employing a complex of herbivorous arthropods that attack different plant parts with synergistic impact on plant reproduction. However, only about 10% of importations against insect pests can be considered truly successful, and this approach is no longer assumed to be an appropriate response to all newly invasive arthropod pests.

Outbreak populations may result when an exotic pest first invades, but then decline over a period of years as the native natural enemy community evolves to exploit them more effectively. This was observed following the invasion of the sorghum aphid in Kansas, which has now receded in importance to levels comparable to other aphid species perennially present in the crop, and despite no specific introductions of biological control agents against it. Many invasive pests ultimately come under adequate biological control solely through the action of native beneficial species, provided the landscape is able to supply them. However, there are also many examples where natural enemies, native or exotic, do not, or cannot, maintain pests below their economic threshold. This does not mean that biological control can be ignored in these contexts, but rather that IPM practices compatible with biological control should be explored, otherwise there is a risk of destabilizing natural control of other pests.

Classical biological control involves exploring a pest's country of origin for a potentially effective natural enemy, importing it to the pest's adopted country, and mass-rearing it in the laboratory for subsequent release in regions where the pest is active. The goal is to establish a self-sustaining population of the natural enemy that continues to maintain the pest population below the economic threshold in perpetuity. Classical biological control differs from other forms of biological control in that it is not carried out by the farmer, but only by scientists with appropriate authorization from federal agencies, in particular the United States Department of Agriculture. Nonnative insects must be held under strict quarantine conditions until it can be ascertained that (1) they have potential to control the target pest, (2) they will not themselves become pests, or damage ecosystems by attacking nontarget species, and (3) they do not harbor any parasitoids or diseases that might hamper their effectiveness or harm other beneficial insects.

Prospective natural enemies must be evaluated for their potential to attack and/or feed on potential alternative prey or beneficial species. Concerns about potential non-target effects of released natural enemies have led to increasingly stringent criteria for introductions, such that generalist predators (species feeding on a broad range of prey) are no longer considered acceptable candidates, and introductions are mostly limited to specialized parasitoids that only attack the target pest. These restrictions are justified given that the broader ecological impacts of introduced species can be complex and exceedingly difficult to predict. A good example is the multicolored Asian lady beetle, *Harmonia axyridis*. Although this species is an excellent biological control agent and a voracious predator of aphids on many crops, it has displaced many native lady beetles from agricultural habitats. It has also become a serious urban pest in many regions, due to its habit of entering buildings in large numbers to escape cold weather. It has also caused serious problems in vineyards where feeds on wine grapes and contaminates the harvest with its pungent chemistry.

Augmentation Biological Control

Since the very beginning of agriculture, farmers have been collecting predatory arthropods such as ants and releasing them in agricultural crops to control pests. Today, many commercially produced natural enemies are released for pest control in greenhouses and organic vegetable production, where they offer an effective and environmentally safe alternative to pesticides. This approach is generally known as augmentation biological control, and is widely recognized by the public because many commercially produced insects are advertised for sale in gardening magazines and online media. Furthermore, the habitual use of pesticides has conditioned people to think about pest management in terms of purchased products that can be applied as needed, but successful augmentation of natural enemies is far more complicated than spraying an insecticide. Augmentation is also less sustainable than other forms of biological control, because it relies on regular or periodic releases of purchased organisms, something that can benefit suppliers of these organisms more than consumers. However, augmentation biological control can be a valuable alternative to chemical insecticides, provided it is both efficacious and cost effective.

Biological control by augmentation is based on the assumption that, although potentially effective natural enemies exist, they are present in insufficient numbers, or their immigration into the crop is not timely enough to provide acceptable levels of pest suppression. Augmentation requires a commercial source of natural enemies that can be purchased quickly in large numbers for an affordable price. In response to demand, many companies have developed insectaries capable of producing large numbers of predatory and parasitic insects, nematodes and microbial pathogens. Unfortunately, while these companies may have developed good techniques for rearing and disseminating their products, they may or may not provide sufficient information on how, where, and when to release these arthropods to obtain good results. Most commercially available natural enemies are only effective against particular pests in specific contexts, and too often supplier recommendations fail to identify circumstances where releases are inappropriate or unlikely to be effective. For example, a predator providing good aphid control on sweet pepper leaves may not do so on tomatoes because the dense leaf hairs (trichomes) impede its foraging behavior.

There are two general release strategies in augmentative biological control: inundative and inoculative. Inundation involves releasing large numbers of natural enemies for immediate reduction of a pest population that is approaching, or already beyond, its economic threshold. This strategy is used mainly for short-term control and is only feasible for natural enemies that can be produced inexpensively in large numbers. It can be considered a rescue treatment, in that successful reproduction and continued survival of the natural enemy population is not expected. Inundative releases may be used as a substitute for a chemical spray that might be undesirable because of unwanted side effects, for example disrupting the biological control of another pest. In contrast, inoculation involves releasing smaller numbers of natural enemies as a preventative measure, usually early in the period of pest activity when it is still at low density, with the expectation that the natural enemy will reproduce and ultimately prevent the pest population from reaching economic levels.

Augmentative biological control is only reliably effective when it rests on a solid foundation of research conducted in the specific context of application. Although responsible purveyors of natural enemies recognize the need to provide an information package with their products to maximize their efficacy, many others are focused on selling insects and expanding markets, resulting in inappropriate applications which can generate consumer dissatisfaction with biological control in general. A prime example is the sale of *Hippodamia convergens* lady beetles to control aphids in urban gardens. Many online outlets offer these insects for sale, including some of the largest agricultural supply companies, despite general agreement among entomologists that they are not effective for this purpose. These adult beetles are collected in buckets *en masse* from overwintering aggregations in the mountains of California. Overwintered females are old, with little egg-laying potential, and as the beetles emerge from hibernation, their instinct is to disperse rather than feed and lay eggs, so most leave the release site immediately, regardless of the presence of aphids. Another problem is that populations reared in an insectary for many generations may become inadvertently domesticated and lose behaviors critical for their effectiveness in more natural settings. Colonies initiated from individuals field-collected from certain localities may be adapted to specific environmental conditions, and if these differ substantially from release sites, their survival and reproduction may be greatly diminished.

Even when an appropriate natural enemy is selected, satisfactory control may not be achieved for several reasons, most often a user's lack of knowledge on the biological requirements of the insect, the life cycle of the target pest, or the appropriate mode of application. Suitable release rates can be difficult to determine for a given situation and depend on many factors, including the pest density at the time of release, and physical conditions such as temperature that will affect the population growth prospects of both pest and natural enemy. Pest managers considering an augmentation approach must obtain as much information as possible to maximize the probability of success. The most successful examples of augmentation biological control in field crops have employed microbial insecticides, especially formulations of insect viruses (nucelopolyhedrosis viruses or NPVs) that are highly specific to important moth pests such as the corn earworm and the fall armyworm.

The cost of commercially supplied natural enemies is a major consideration in assessing their potential suitability as a pesticide alternative. Prices vary widely because of differences in the degree of difficulty and expense in rearing different species. The quality or condition of the organisms also can vary significantly among insectaries. It can be justifiable to pay a higher cost for a natural enemy in situations where pests have evolved insecticide resistance, where worker protection standards are a concern, where insecticides risk disrupting biological control of other pests, or where certified organic production will yield a premium price. In general, augmentation biological control programs are most often justified on high-value fruit and vegetable crops.

Important questions to ask before considering an augmentation program:

1. Has research shown that a release program can be effective for a particular pest, crop and local situation?
2. What is the best time to release the natural enemy in relation to the pest's life cycle?
3. Are releases compatible with other crop production practices that are anticipated, including the possible need to apply pesticides against other pests?
4. Does the supplier provide a comprehensive information package with clear instructions on handling, releasing, and evaluating the effectiveness of the natural enemy?
5. What quality control practices does the supplier use to ensure that insects arrive alive and in good condition?
6. How does the overall cost of a release program compare with alternative control strategies when all ancillary costs and benefits are factored in?

In summary, although augmentation is perhaps the most publicly recognized form of biological control, it is also one of the least understood and most often misapplied. Although it can provide a safe alternative for controlling certain pests, a significant research investment is required to obtain reliable results, and there exist many inappropriate applications for every suitable one. The end user must obtain and assimilate the relevant information necessary to effectively implement a release program, and ensure that the product purchased is appropriate for the particular pest and situation. Currently, only microbial products can be recommended for augmentation biological control on any large scale in Kansas field crops.

Natural Enemies in Kansas Field Crops

Predators

Predators are insects or other arthropods (spiders and mites) that feed on pests by hunting, killing and directly consuming them. Although more than 100 families of insects contain predaceous species, only about 12 contain important biological control agents of field crop pests.

Lady Beetles (Coleoptera: Coccinellidae)

Lady beetles, or ladybugs, are possibly the most universally recognized group of beneficial insects. Most species have larval stages that resemble little alligators, and adults are usually brightly colored (to advertise the fact they are distasteful to birds) with slightly clubbed ends on their antennae. They can be found almost anywhere, feeding on aphids and a variety of soft-bodied insects, including mites and the eggs and small larvae of moths and beetles.

One of the most abundant species in Kansas field crops is the convergent lady beetle, *Hippodamia convergens*, a native species. This lady beetle is recognizable by the two convergent white lines on the pronotum, the portion of the body immediately behind the head (Figure 1). Coloration ranges from pale orange to red with a series of black spots on the elytra (wing covers) that may be only faintly visible, or entirely absent. Female convergent lady beetles require aphids to elicit reproduction, although both adults and larvae will supplement their diet with many other prey items, along with the pollen and nectar of flowers. Overwintered adults complete their first generation in early spring, typically around wheat harvest, leading to the mass exodus of large numbers of beetles from maturing wheat fields. First-generation females mate within days of emergence, but will not mature eggs immediately. Rather, the energy gleaned from any prey consumed is stored in fat bodies, and reproduction does not occur until plentiful aphids are found, sometimes not until autumn. These beetles are extremely drought tolerant

Figure 1. The convergent lady beetle is an aphid specialist, and one of the most abundant species in Kansas.

and survive dry periods by obtaining moisture from plant sources, such as the extrafloral nectar produced by sunflowers. If aphid populations develop on corn, sorghum or soybeans, the smell of honeydew excreted by aphids will attract adult beetles and, after three to four days of gorging on aphids, females will lay their bright yellow or orange eggs in clusters, usually under the lower leaves of infested plants. As fall brings cooler weather, aphid populations can increase on senescing plants, providing beetles with a final opportunity to produce another generation that will overwinter as adults. Therefore, the number of generations is variable, depending on the food supply, and most adults maturing late in the season conserve their resources for hibernation. They crawl into protected sites, typically at the base of grass tussocks, and remain dormant through winter months until they are awakened by the warm temperatures of spring. These abilities to hibernate in winter and forgo reproduction during summer when prey are scarce represent adaptations that are key to this species' success and abundance in prairie habitats.

Another common species is the twelve-spotted lady beetle, *Coleomegilla maculata*. The adults are pink with six black spots on each wing cover (Figure 2). Aphids are the preferred food of this species, but the beetles also consume a wide range of insect prey, and unlike the convergent lady beetle, they can reproduce without aphids. The larvae of this species can complete development only on pollen, provided they have sufficient moisture. Adults are attracted to corn fields at tasseling, where they feed on corn pollen and the eggs and small larvae of many moth species, including corn borers and corn earworms. This species has three or four generations per year and

Figure 2. The twelve-spotted lady beetle is a generalist, feeding on aphids and the eggs and larvae of various pests.

Figure 3. The Asian ladybeetle is an invasive species, but also an effective predator of a wide range of pests.

Figure 4. The seven spotted lady beetle is originally from Europe, and a frequent presence in wheat fields.

Figure 5. *Scymnus* spp. ladybeetles are often overlooked because of their small size.

is often found in proximity to water sources such as rivers and lakes. The species is not nearly as drought tolerant as the convergent lady beetle and has a high water demand during both larval and adult stages, so it tends to be more abundant in wet years. During winter months, aggregations can be found hibernating under piles of old lumber and other sheltered sites.

The multicolored Asian lady beetle, *Harmonia axyridis*, is an adventive species that became common in the Midwest following the invasion of soybean aphids at the turn of the century (Figure 3). Adults are highly variable in coloration (pale orange to red) and spotting patterns (many spots, or none). The key to identifying this species is the prominent black W on the pronotum (part of the body behind the head). This invasive species is a voracious predator of aphids and many other insects, including the larvae of the alfalfa weevil. Unfortunately, it also feeds on the eggs and larvae of other lady beetles and has been implicated in the declining abundance of a number of native species in crop fields. Although it can be an effective biological control agent in many agricultural contexts, it can be a pest in fruit crops and a serious contaminant in wine grapes. It also has a propensity for entering houses in fall and winter, often forming large aggregations that can be distressing to homeowners.

Figure 6. Larvae of *Scymnus* spp. excrete a waxy covering that protects them from attacks by ants.

Figure 7. *Stethorus* spp. are specialized predators of mites.

The seven spotted lady beetle, *Coccinella septem-punctata*, is another imported species that originated in Europe. This is the largest species of lady beetle in Kansas, and it can be recognized by the distinctive seventh black spot that spans the front edge of both wing covers and is flanked by two small white triangles (Figure 4). The larvae require aphids to complete development, and the species can be abundant in wheat in the spring.

Several smaller species of lady beetles can also be abundant in Kansas fields, but it may go unnoticed because of their small size and more secretive habits. Many are important predators of moth eggs, spider mites, and thrips. *Scymnus* spp. (Figure 5) have larvae that produce waxy secretions that protect them from ant predation, causing them to resemble mealybugs (Figure 6). Others such as *Stethorus* spp. are even smaller and specialize in feeding on mites (Figure 7).

Hover Flies (Diptera: Syrphidae)

Hover flies (Figure 8) are also known as flower flies and are most easily recognized by their hovering flight above flowers or aphid-infested plants. Many resemble bees or wasps, but there is great variation among species in size and appearance. The larvae (Figure 9) are voracious predators of aphids and some other soft-bodied insects. Adult hover flies require access to flowers, as nectar is an important food source, and females must consume pollen as a protein source before they can mature eggs. Adult females orient to the smell of honeydew excreted by aphids and then assess aphid colonies visually. They can be among the first natural enemies to discover aphid colonies while the colonies are still small and vulnerable to predation. Many studies have shown that planting mixed borders of wildflowers around gardens can attract hover flies and improve aphid control on adjacent vegetables and other crops. Organic production of broccoli and lettuce is now accomplished by intercropping with sweet alyssum, which attracts hover flies in sufficient numbers to keep aphids under control. This is an example of conservation biological control by habitat management and is the most effective means of encouraging these insects.

Different species of hover fly are selective in the kinds of aphids they exploit, and some are quite specific to certain aphid species on particular plants. The white, oblong eggs (Figure 10) are usually laid singly in among the aphids. A maggot hatches in two or three days and begins to feed on aphids voraciously, growing at a truly remarkable rate. The larvae are slug-like, tapered toward the head, and adhere to the leaf surface in a film of their own saliva. Syrphid larvae pass through three instars and may form pupae

Figure 8. Many hoverflies mimic the appearance of wasps.

Figure 9. Hoverfly larvae are voracious aphid predators, consuming as many as 300-400 in about a week.

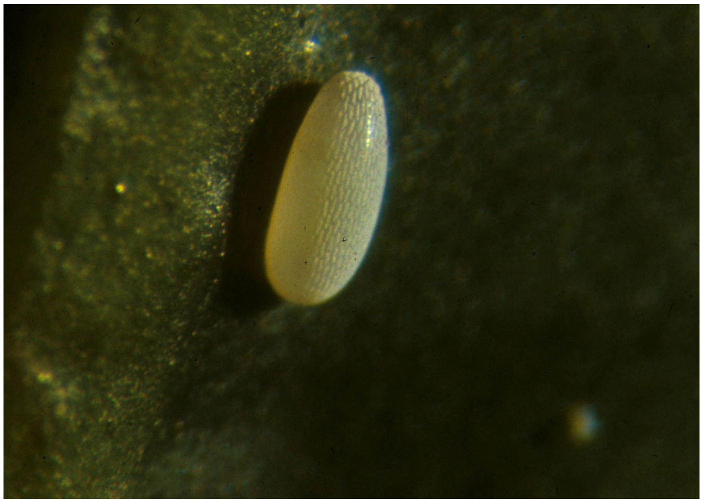

Figure 10. Hoverfly eggs are often laid on nascent aphid colonies while the colonies are still very small.

Figure 11. Hoverfly pupae typically form away from the aphid colony, and are the overwintering stage.

within seven to 14 days, depending on temperature, consuming as many as 400 to 500 aphids to complete development. The pupae are typically teardrop-shaped (Figure 11) and may form on plant parts below the aphid colony, or in the soil, depending on species. The pupa is also the overwintering stage. Syrphid flies are important, if often overlooked, aphid predators that help keep populations below damaging levels in many crops.

Lacewings (Neuroptera: Chrysopidae and Hemerobiidae)

All lacewings are predaceous as larvae, but adults of some species are predaceous as well. Lacewing larvae (Figure 12) prefer aphids as prey, but also consume a range of other soft-bodied pests such as mites, thrips, leafhoppers, and mealybugs. The most common species in Kansas field crops is the green lacewing, *Chrysoperla carnea*, which is considered to be a complex of different species that are difficult to distinguish. Adults have large, lacey wings, thread-like antennae, and protruding eyes (Figure 13). They are primarily nocturnal, but when disturbed, they leave their resting places on the undersides of leaves in an erratic, fluttering flight. Despite their fragile appearance, lacewings are among the very few insects capable of extricating themselves from a spiderweb. The white, oval eggs of green lacewings are laid on the end of long stalks (Figure 14), whereas those of brown lacewings are darker in color and lack stalks. The relative length of the stalk and the pattern in which the eggs are laid (singly versus in groups, in line or in a spiral) can be characteristic of particular green lacewing species.

Figure 12. Green lacewing larvae are primarily aphid predators, but will consume many other soft-bodied insects.

Lacewings are among the beneficial insects that are available commercially. Usually, the eggs are shipped mixed with a substrate such as rice hulls and some moth eggs for food. However, the larvae are highly cannibalistic and immediately begin to kill and eat each other upon hatching, so they require immediate distribution in the field. Even then, a lack of reliable information on habitat preferences, climatic tolerances, dormancy, and behavioral responses in different settings, as well appropriate release rates and release techniques, have severely limited the usefulness of these insects for augmentation biological control in open fields. Fortunately, they are naturally abundant in summer field crops, where they make an important contribution to pest control.

True Bugs (Hemiptera: Anthocoridae,

Figure 13. Adult green lacewings are primarily nocturnal, resting underneath leaves in the daytime.

Figure 14. The eggs of green lacewings are laid on the end of long stalks, which helps protect them from predation.

Nabidae)

Numerous species of true bugs are predators of insect pests. These include damsel bugs, (*Nabis* spp., Figure 15), big-eyed bugs (*Geocoris* spp.), minute pirate bugs (*Orius* spp.) and assassin bugs such as the wheel bug (Reduviidae). The spined soldier bug (Figure 16) is a valuable predator of caterpillars, even though it belongs to the stink bug family (Pentatomidae), many of which are serious plant pests. Predatory bugs skewer their prey with piercing and sucking mouthparts, inject enzymes to digest the internal organs, and then drink the liquefied body contents like soup through a straw. This process is known as extraoral digestion and is also used by lacewing larvae. A wide range of prey are taken depending on the size and species of bug. Minute pirate bugs are partial to thrips, but also feed on aphids, caterpillars, and insect eggs. Larger assassin bugs (Reduviidae) such as the wheel bug (Figure 17) are ambush predators at the top of the food chain and feed on many kinds of insects, even other beneficial species such as lady beetles. This is an example of intraguild predation – predators eating each other as well as feeding on pest species, a phenomenon that complicates, but does not necessarily disrupt, biological control processes.

Ground Beetles (Coleoptera: Carabidae)

More than 20 species of ground beetles are commonly found in all Kansas field crops. Both larvae and adults are predaceous on many ground-dwelling insects, making them important predators of many surface-dwelling arthropods. Most species are large, shiny and black, with ridged wing covers, and some have

Figure 15. Damsel bugs are generalist predators common in many crop fields.

Figure 16. The spined soldier bug is generalist predator with a preference for caterpillars.

Figure 17. Assassin bugs are ambush predators that feed on many insects, including beneficial species.

Figure 18. *Lebia* sp. are small ground beetles that, unlike other Carabidae, will climb up onto plants in search of prey.

iridescent coloration. They have threadlike antennae and a head that is usually much smaller than the thorax (part behind the head). Adults of most species are flightless and are typically seen running across the soil surface. Most adults feed on caterpillars and other soft-bodied insects they find on the soil surface, whereas most larvae feed on insects such as maggots and rootworms within the soil. Although most ground beetles do not climb plants, they contribute to biological control of cereal aphids, because predators often dislodge more aphids from plants than they eat, and ground beetles foraging on the soil surface reap the rewards, ensuring that dislodged aphids cannot climb back onto the plants. Small ground beetles of the genus *Lebia* (Figure 18) are an exception, and these beetles can often be found searching for prey up in the crop canopy.

Spiders

Although spiders are not insects, they play an important role as generalist predators of many insect groups, and their importance as biological control agents is perhaps greater than previously thought. An abundance of spiders is considered by many to be indicative of a healthy agroecosystem. Spiders comprise a very diverse group that can be broadly categorized by their hunting strategies. Web-spinners, including orb-weavers, and garden spiders, use silk to trap their prey in various ways. Species such as crab spiders are highly cryptic sit-and-wait predators that hide in flowers to ambush pollinators and other flower visitors. Hunting spiders are typically hairy, robust species that do not build webs, but actively seek out their prey on plants or on the soil surface. These include jumping spiders, wolf spiders and the large tarantulas. Spiders in general are sensitive to high temperatures, so they prefer crop habitats that provide shade and forms of shelter, like crop residues.

Parasitoids

Parasitoids are the vampires of the insect world. In their larval stages, they obtain nutrients by feeding in or on the body of another insect, ultimately killing it. The adults are typically free-living, the females seeking out suitable host insects for their progeny. The two major groups are parasitoid wasps and tachinid flies.

Parasitoid Wasps

Parasitoid wasps comprise one of the most diverse and important groups of beneficial insects. Almost all insects are attacked by at least one species of parasitoid, and most are attacked by more than one. Some species are highly specific and attack only one host species, and many successful classical biological control programs have involved the introduction of such parasitoids. Some species are large and colorful, but most of the economically important ones are small and inconspicuous. For example, parasitoids attacking aphids are smaller than their aphid hosts (Figure 19), and those developing within a single moth egg or scale insect are barely visible to the naked eye. Some species are solitary, with only a single individual completing development in a host insect, whereas others are gregarious, with as many as 40 to several hundred siblings feeding and developing on the same host.

Parasitoid wasps have haplodiploid sex determination; because males are produced from unfertilized eggs, and females from fertilized ones, females can manipulate the sex of their progeny by controlling egg fertilization. In some species, uniparental (all-female) lines persist for many generations without sexual reproduction. The female wasp uses an ovipositor to lay eggs in a host insect (the stinger of a honey bee worker is a modified ovipositor that delivers only venom). In some species the ovipositor is held internally when not in use; in others it is not retractable and may be as long, or longer than, the entire wasp body. Venom is delivered via the ovipositor that serves to immobilize, paralyze or otherwise subdue the host. Some female parasitoids host feed, using

Figure 19. Aphid parasitoids in the family Braconidae can each parasitize several hundred aphids in a few days.

the ovipositor to puncture a host and then feed on the body fluids before proceeding to lay eggs in other hosts, thus causing two different types of mortality in the pest population. In some cases, the egg is laid externally on the body of the host and the larvae may also feed externally (ectoparasitism). More commonly, the larva develops and pupates within the host body, feeding selectively on the host's internal tissues, and usually leaving the digestive tract and nervous system intact until the very end (endoparasitism). Another important distinction is whether the host is allowed to develop and grow with the parasitoid larva inside it (a koinobiont strategy), or whether it is killed or permanently paralyzed by the attack so that it remains a static, rather than dynamic, food source for the developing larva (an idiobiont strategy).

Tachinid Flies

This group represents a very large family of flies with more than 1,000 species in North America, all of which have a parasitic lifestyle. They vary considerably in appearance, but most resemble house flies with very bristled bodies, although they can be substantially larger or smaller (Figure 20). Adult females may lay an egg on the surface of the host insect cuticle. The hatching larva then bores into the body of the host and develops internally. In other species, the fly lays eggs on plant leaves that are then consumed by the host insect, whereas others deposit larvae that then seek out their host, often within a hole or tunnel in the plant. A wide range of moth and butterfly larvae are attacked, as are some beetle species. The host may be killed in the adult stage, but more commonly the adult fly emerges from the pupal stage.

Figure 20. Tachinid flies typically have hairy abdomens and are important parasitoids of grubs and caterpillars.

Nematodes

Nematodes are a phylum of roundworms that are among the most abundant multicellular organisms on earth. Many families of nematodes feed on plants and include many important pest species. Some species are free-living, whereas others are obligate parasitoids of insects and include many important biological control agents. Some are produced and sold commercially for control of soil and foliar insects. Nematodes are normally applied as either a spray suspension or a soil drench, but their survival and efficacy is often dependent on soil type and adequate moisture. They are associated with various commensal and symbiotic bacteria that aid them in killing and digesting their host insects. Recently, gel formulations have been developed that protect infective juvenile stages from desiccation so they can be applied to above-ground plant parts.

Microbial Pathogens

A variety of microbial pathogens, including bacteria, protozoans, viruses and fungi, are specifically pathogenic to insects and completely harmless to other forms of life. This selective pathogenicity renders many of them valuable as biological control agents of insect pests. Insect diseases caused by pathogens can be important sources of pest mortality that lead to precipitous population declines when they become epizootic (analogous to an epidemic in a human population). However, attempts to induce epizootics in pest populations by distributing spores or other types of inoculum in crop fields fail because stringent conditions can be necessary for successful infection and/or transmission of the disease. For example, many fungal diseases of insects require high humidity or prolonged leaf wetness in combination with particular temperatures to infect their hosts. Recently, success has been obtained using commercially formulated baculoviruses against fall armyworms and corn earworms on a variety of crops. Many insect epizootics proceed without human assistance when suitable environmental conditions arise, and conservation alone can be a valuable approach when epizootics cause significant mortality in pest populations. For example, the use of fungicides to control foliar diseases can also eliminate insect-pathogenic fungi, thus favoring pest outbreaks.

Conclusions

Biological control is a natural process that plays an important role in the suppression of field crop pests, often proceeding unnoticed by the farmer, simply because both the pest and its natural enemies coexist at such low densities that no problem is perceived in the crop. This fact has been demonstrated repeatedly by using pesticide treatments to disrupt natural enemy populations so that formerly insignificant insects rise to the status of major pests. It is generally agreed that integrated pest management (IPM) is the preferred approach to sustainable agricultural pest control, and that whenever possible, IPM programs for field crops should be established on a foundation of biological control, with chemical control measures applied judiciously to conserve natural enemies and all nontarget insects to the greatest extent possible. The best way a farmer can benefit from biological control, and avoid the expense and hazards of pesticide applications, is by learning to recognize and conserve the beneficial insects that feed on the key pests attacking his crops. These insects should be thought of as free farm labor – the only wages they demand are a source of food, i.e., the pests that they consume. The requirements of many beneficial species are well understood, and many techniques are available to conserve natural enemies and encourage their activities. For example, no-till agriculture has been shown to have a net positive effect on the abundance of beneficial insects in field crops. Crops genetically modified to express natural insect toxins have proven either neutral or favorable to biological control, and have generally reduced overall pesticide usage. Marginal areas around fields can serve as reservoirs of many natural enemies, especially if they contain perennial flowering plant species. Limiting pesticide treatments to affected spots in a field and leaving less-affected portions untreated will provide refuges for natural enemies and accelerate the field-wide restoration of biological control posttreatment. Various new pesticide formulations have far more selective modes of action than older materials and will spare natural enemies. In short, whenever biological control has a role in regulating pest populations, pest control decisions should be weighted by considerations of how natural enemies will be impacted, and what tactics might be feasible to conserve them.

Photo Credits

Figs. 1, 2, 3: J.P. Michaud
Fig. 5: Stephen Luk
Fig. 6: University of Idaho
Figs. 7, 19: U. Wyss
Fig. 8: Kim Davis
Figs. 4, 9, 10, 11, 20: unknown
Fig. 12: E. Prado
Fig. 13: R.K.D. Peterson
Fig. 14 : P.E. Sloderbeck
Fig. 15: Winston Beck
Fig. 16: W. Sterling
Fig. 17. Richard Orr
Fig. 18: Shanon Schade

J.P. Michaud
Professor of Entomology, Kansas State University

K·STATE
Research and Extension

Publications from Kansas State University are available at *bookstore.ksre.ksu.edu*.

Kansas State University Agricultural Experiment Station and Cooperative Extension Service
K-State Research and Extension is an equal opportunity provider and employer. Issued in furtherance of Cooperative Extension Work, Acts of May 8 and June 30, 1914, in cooperation with the U.S. Department of Agriculture, Director of K-State Research and Extension, Kansas State University, County Extension Councils, Extension Districts.