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Designing and Implementing a Habitat Management Strategy to Enhance Biological Pest Control in Agroecosystems

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Farmers can enhance the resistance and resilience of their crops and fields by reinforcing their built-in defenses against pests. This can be done by following two main strategies: increasing above- and below-ground biodiversity and improving soil health. This paper focuses on the role of beneficial insect biodiversity in farms, and on the ways of enhancing functional biodiversity in agroecosystems as a means of promoting biological control of insect pests.

Biodiversity is crucial to crop defenses: the more diverse the plants, animals and soil-borne organisms that inhabit a farming system, the more diverse the community of pest-fighting beneficial organisms the farm can support. One group of partners – *beneficial predators* – chew up plant-eating insects and mites or sucks out their juices. Another group – *beneficial parasites* – lay eggs inside pest eggs and/or larvae. A third group – *beneficial disease-causing organisms* that include fungi, bacteria, viruses, protozoa and nematodes – fatally sicken pests or keep them from feeding or reproducing. Plants also form complex associations with organisms around their roots, which offer protection against disease. Soil fungi and ground beetles can destroy the seeds of weeds that compete with plants. In addition the rich soil fauna play key roles in breaking up and decomposing organic matter thus making nutrients available to plants. Biodiversity in the form of polycultures may also make plants less "apparent" to pests; crops growing in monocultures may be so obvious to pests that the plants' defenses fall short of protecting them.

Farmers can enhance biodiversity on their farms by:

- increasing plant diversity with crop rotations or with

"polycultures" of cash and cover crops grown on the same land at the same time;
- managing vegetation surrounding fields to meet the needs of beneficial organisms;
- providing beneficial organisms with supplemental resources, such as artificial nesting structures, extra food and alternative prey;
- designing "corridors" of plants that usher beneficials from nearby forests or natural vegetation to field centers
- selecting non-crop plants grown as strips in fields, whose flowers match beneficials' requirements.

Healthy soils are also essential to plant defenses. Unhealthy soils hinder crops' abilities to use their natural defenses and leave them vulnerable to potential pests. In contrast, healthy soils arm plants chemically with defense-boosting nutrients and are physically conducive to optimum root development and water use. Reduced susceptibility to pests is usually a reflection of differences in plant health as mediated by soil fertility management. Many studies document lower abundance of several insect pests in low-input systems and they attribute partly such reductions to the lower nitrogen content of organically farmed crops. In addition, the rich supplies of beneficial organisms that inhabit healthy soils can intensify nutrient uptake, release growth-stimulating chemicals and antagonize disease-causing organisms. Healthy soils can also expose weed seeds to more predators and decomposers, and their slower release of nitrogen in spring can delay small-seeded weeds – which often need a flush of nitrogen to germinate and begin rapid growth – thereby giving larger-seeded crops a head start.

Farmers can improve soil health by:
- diversifying crop rotations including legumes and perennial forages
- keeping soils covered year-round with living vegetation and/or crop residue
- adding plenty of organic matter from animal manures, crop residues and other sources
- reducing tillage intensity and protecting soils from erosion and compaction
- using best-management techniques to supply balanced nutrients to plants without polluting water

When farmers adopt agricultural practices that increase the abundance and diversity of above- and below-ground organisms, they strengthen their crops' abilities to withstand pests. In the process, farmers also improve soil fertility and crop productivity.

Biodiversity in farms and its function

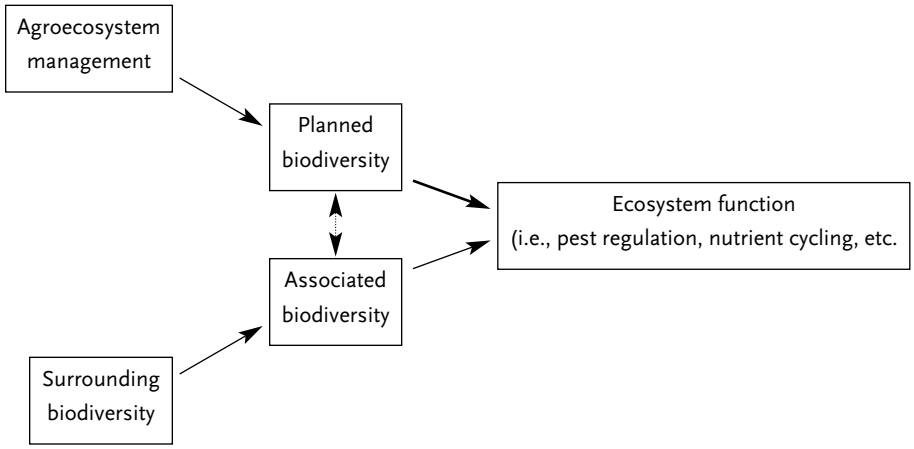
Biodiversity in farms refers to all plant and animal organisms (crops, weeds, livestock, natural enemies, pollinators, soil fauna, etc) present in and around farms. Biodiversity can be as varied as the various crops, weeds, arthropods, or microorganisms involved, according to geographical location, climatic, edaphic [soil-related], human, and socioeconomic factors. In general the degree of biodiversity in agroecosystems depends on four main characteristics of the agroecosystem:
- the diversity of vegetation within and around the agroecosystem;
- the permanence of the various crops within the agroecosystem;
- the intensity of management;
- the extent of the isolation of the agroecosystem from natural vegetation.

How diverse is the vegetation within and around the farm, how many crops comprise the rotation, how close is the farm to a forest, hedgerow, meadow or other natural vegetation, are all factors that contribute to a particular farm's level of biodiversity.

The biodiversity components of farms can be classified in relation to the role they play in the functioning of cropping systems. According to this, agricultural biodiversity can be grouped as follows:
- productive biota: crops, trees, and animals chosen by farmers that play a determining role in the diversity and complexity of the agroecosystem;
- resource biota: organisms that contribute to productivity through pollination, biological control, decomposition, etc;
- destructive biota: weeds, insect pests, microbial pathogens, etc., which farmers aim at reducing through cultural management.

Two distinct components of biodiversity can be recognized in agroecosystems. The first component, *planned biodiversity,* includes the crops and livestock purposely included in the agroecosystem by the farmer, and which will vary depending on the management inputs and crop spatial/temporal arrangements. The second component, *associated biodiversity,* includes all soil flora and fauna, herbivores, carnivores, decomposers, etc. that colonize the agroecosystem from surrounding environments and that will thrive in the agroecosystem depending on its management and structure. The relationship of both types of biodiversity components is illustrated in Figure 1. Planned biodiversity has a direct function, as illustrated by the bold arrow connecting the planned biodiversity box with the ecosystem function box. Associated biodiversity also has a function, but it is mediated through planned biodiversity. Thus, planned biodiversity also has an indirect function, illustrated by the dotted arrow in the figure, which is real-

Figure 1. Relationships between several types of biodiversity and their role in agroecosystem function



ized through its influence on the associated biodiversity. For example, the trees in an agroforestry system create shade, which makes it possible to grow only sun-intolerant crops. So, the direct function of this second species (the trees) is to create shade. Yet along with the trees might come wasps that seek out the nectar in the tree's flowers. These wasps may in turn be the natural parasitoids of pests that normally attack crops. The wasps are part of the associated biodiversity. The trees then create shade (direct function) and attract wasps (indirect function).

Complementary interactions between the various biodiversity components can also be of a multiple nature. Some of these interactions can be used to induce positive and direct effects on the biological control of specific crop pests, soil fertility regeneration and/or enhancement and soil conservation. The exploitation of these interactions in real situations involves novel farm designs and management and requires an understanding of the numerous relationships between soils, microorganisms, plants, insect herbivores, and natural enemies. In fact the optimal behavior of agroecosystems depends on the level of interactions between the various biotic and abiotic components. By assembling a functional biodiversity (that is a collection of interacting organisms that play key functions in the farm) it is possible to initiate synergisms which subsidize farm processes by providing ecological services such as the activation of soil biology, the recycling of nutrients, the enhancement of beneficial arthropods and antagonists, and so on, all important in determining the sustainability of agroecosystems (Figure 2).

In modern agroecosystems, the experimental evidence suggests that biodiversity can be used for improved pest management. Several studies have shown that it is possible to stabilize the insect communities of agroecosystems by designing diverse cropping systems that support populations

Figure 2. Components, functions and strategies to enhance functional biodiversity in agroecosystems

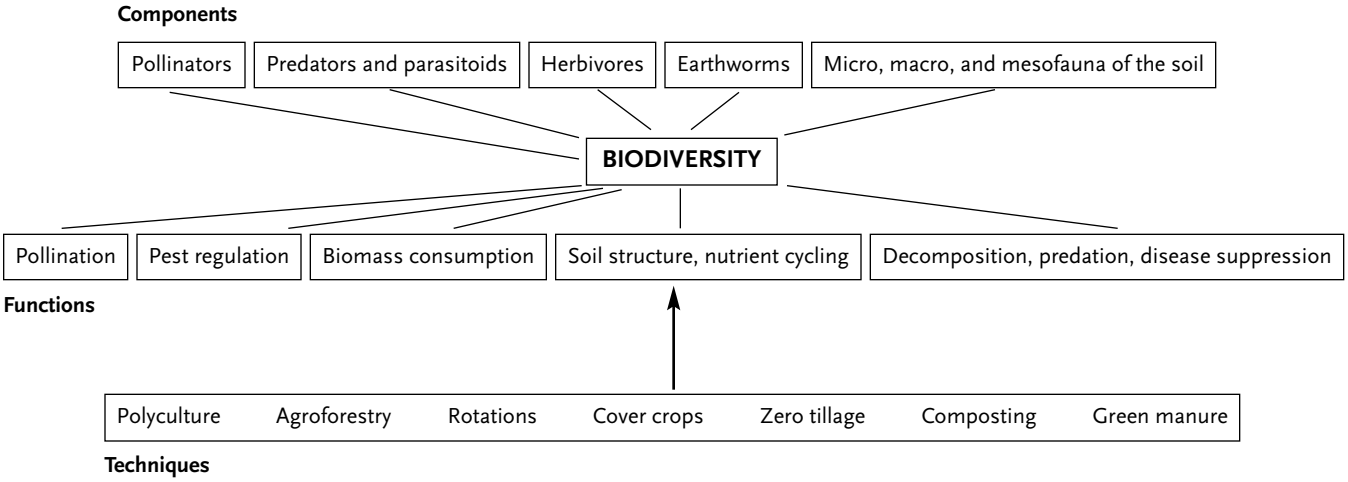
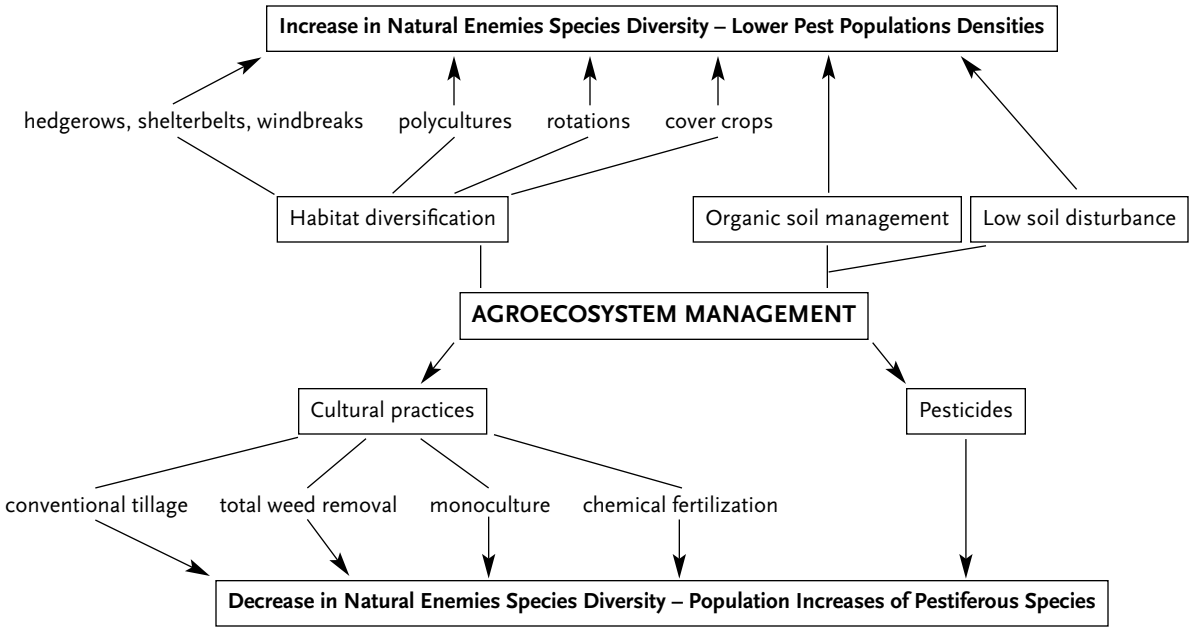


Figure 3. The effects of agroecosystem management and associated cultural practices on the diversity of natural enemies and the abundance of insect pests



of natural enemies or have direct deterrent effects on pest herbivores. The key is to identify the type of biodiversity that is desirable to maintain and/or enhance in order to carry out ecological services, and then to determine the best practices that will encourage the desired biodiversity components. There are many agricultural practices and designs that have the potential to enhance functional biodiversity, and others that negatively affect it. The idea is to apply the best management practices in order to enhance or regenerate the kind of biodiversity that can subsidize the sustainability of agroecosystems by providing ecological services such as biological pest control, nutrient cycling, water and soil conservation, etc. The role of farmers and researchers should be to encourage those agricultural practices that increase the abundance and diversity of above- and below-ground organisms, which in turn provide key ecological services to agroecosystems (Figure 3).

Thus, a key strategy in farming is to exploit the complementarity and synergy that result from the various combinations of crops, trees, and animals in agroecosystems that feature spatial and temporal arrangements such as polycultures, agroforestry systems and crop-livestock mixtures. In real situations, the exploitation of these interactions involves farming system design and management and requires an understanding of the numerous relationships among soils, microorganisms, plants, insect herbivores, and natural enemies.

Biological pest control: a strategy to increase biodiversity in farms

Studies show that farmers can indeed bring pests and natural enemies into balance on biodiverse farms. One of the most powerful and long-lasting ways to keep pests from causing economic damage on your farm is to boost existing or naturally occurring beneficial organisms to effective levels by supplying them with appropriate habitat and alternative food sources. Fewer beneficial organisms – predators, parasites and pest-sickening "pathogens" – live in monocultures or in fields routinely treated with pesticides than on more diverse farms where fewer pesticides are used. In general farms sharing many of these characteristics host bountiful beneficials:

- fields are small and surrounded by natural vegetation;
- cropping systems are diverse and plant populations in or around fields include perennials and flowering plants;
- crops are managed organically or with minimal synthetic agrichemicals;
- soils are high in organic matter and biological activity and – during the off-season – covered with mulch or vegetation.

Naturally occurring beneficials, at sufficient levels, can take a big bite out of pest populations. To exploit them effectively, farmers must:

- identify which beneficial organisms are present;
- understand their individual biological cycles and resource requirements.

With this information, farmers can devise management schemes that will increase the size and diversity of natural-enemy complexes and decrease pest problems.

Predators

Biodiverse farms are rich in predatory insects, spiders and mites. These beneficial arthropods prey on other insects and spider mites, and are critical to natural biological control. Most predators are "generalist" feeders, attacking a wide variety of insect species and life stages. Predators occur in most orders of insects but primarily in *Coleoptera, Odonata, Neuroptera, Hymenoptera, Diptera and Hemiptera.* Their impacts have been highlighted worldwide by eruptions of spider mite pests where chemical insecticides have eliminated the mites' predators. Tetranychid mites, for example, are usually very abundant in apple orchards where pesticides have destroyed natural predator populations.

The diversity of predator species in particular agroecosystems can be impressive. Researchers have reported more than six hundred species – from forty-five families – of predaceous arthropods in Arkansas cotton fields and about 1,000 species in Florida soybean fields. Such diversity can apply major regulatory pressures on pests. Indeed, many entomologists consider native, or indigenous, predators a sort of balance wheel in the "pest-natural enemy complex" because they tend to feed on whatever pest is overabundant. Even where predators can't force pest populations below economically damaging levels, they can and do slow down the rate at which potential pests increase. In spray-free apple orchards in Canada, five species of predaceous true bugs were responsible for 44 to 68 percent of the mortality of codling moth eggs.

Major characteristics of arthropod predators:

- Adults and immatures are often generalists rather than specialists
- They generally are larger than their prey
- They kill or consume many prey
- Males, females, immatures, and adults may be predatory
- They attack immature and adult prey
- They require pollen and nectar and additional food resources

Parasitoids

Most parasitoids – parasitic insects that kill their hosts – live freely and independently as adults; they are lethal and dependent only in their immature stages. Parasitoids can be specialists, targeting either a single host species or several related species, or they can be generalists, developing in many types of hosts. Typically, they attack hosts larger than themselves, eating most or all of their hosts' bodies before pupating inside or outside them. With their uncanny ability to locate even sparsely populated hosts using chemical cues, parasitoid adults are much more efficient than predators at ferreting out their quarry.

Most parasitoids used in the biological control of insect pests are either *Diptera* flies – especially from the family *Tachinidae* – or *Hymenoptera* wasps from the superfamilies *Chalcidoidea, Ichneumonoidea, and Proctotrupoidea.* Parasitoid diversity is directly related to plant diversity: different crops, ground covers, weeds and adjacent vegetation support different pests, which in turn attract their own groups of parasitoids. In large-scale monocultures, parasitoid diversity is suppressed by vegetational simplification; in less-disturbed and pesticide-free agroecosystems, it is not unusual to find eleven to fifteen species of parasitoids hard at work. In many cases, just one or two species of parasitoids within these complexes prove vital to the natural biological control of primary insect pests. In California's alfalfa fields, the braconid wasp *Cotesia medicaginis* plays a pivotal role in regulating the alfalfa caterpillar. This pristine butterfly-wasp system apparently moved into irrigated alfalfa from native clovers.

Major characteristics of insect parasitoids:

- They are specialized in their choice of host
- They are smaller than host
- Only the female searches for host
- Different parasitoid species can attack different life stages of host
- Eggs or larvae are usually laid in, on, or near host
- Immatures remain on or in host; adults are free-living, mobile, and may be predaceous
- Immatures almost always kill host
- Adults also require pollen and nectar

Enhancing beneficial insects by designing biodiverse farms

Natural enemies do not fare well in monocultures. Normal cultural activities like tilling, weeding, spraying and harvesting take their toll, and overly simplified systems lack many of the resources essential to beneficials' survival and reproduction.

To complete their life cycles, natural enemies need more than prey and hosts: they need refuge sites and alternative food, hosts and prey which are usually absent in monocultures. For

example, many adult parasites sustain themselves with pollen and nectar from nearby flowering weeds while searching for hosts. Predaceous ground beetles – like many other natural enemies – do not disperse far from their overwintering sites: access to permanent habitat near or within the field gives them a jump-start on early pest populations.

Farmers can minimize the disruptive impacts of modern crop production by understanding and supporting the biological needs of natural enemies. With this same knowledge, they can also design crop habitats that are friendlier to natural enemies.

Improving crop habitats for natural enemies

To conserve and develop rich complexes of natural enemies, farmers should avoid cropping practices that harm beneficials. Instead, they should substitute methods that enhance their survival. Start by reversing practices that disrupt natural biological control: these include insecticide applications, hedge removal and comprehensive herbicide use intended to eliminate weeds in and around fields.

Providing supplementary resources

Natural enemies benefit from many kinds of supplementary resources. In North Carolina, erecting artificial nesting structures for the red wasp *Polistes annularis* intensified its predation of cotton leafworms and tobacco hornworms. In California alfalfa and cotton plots, furnishing mixtures of hydrolyzate, sugar and water multiplied egg-laying by green lacewings six-fold and boosted populations of predatory syrphid flies, lady beetles and soft-winged flower beetles.

Farmers can increase the survival and reproduction of beneficial insects by allowing permanent populations of alternative prey to fluctuate below damaging levels. Use plants that host alternative prey to achieve this: plant them around your fields or even as strips within your fields. In cabbage, the relative abundance of aphids helps determine the effectiveness of the general predators that consume diamondback moth larvae. Similarly, in many regions, anthrocorid bugs benefit from alternative prey when their preferred prey, the western flower thrip, is scarce.

Another strategy – enhancing levels of a beneficial's preferred host – has controlled cabbage white butterflies in cole crops. Supplemented with continual releases of fertile females, populations of this pest escalated nearly ten-fold in spring. This enabled populations of two of its parasites – *Trichogramma evanescens* and *Apanteles rebecula* – to build up early and maintain themselves at effective levels all season long. Because of its obvious risks, this strategy should be restricted to situations where sources of pollen, nectar or alternative prey simply can't be obtained.

Increasing within-field plant diversity

By diversifying plants within agroecosystems, farmers can expand environmental opportunities for natural enemies and thereby improve biological pest control. One way to do this is to plant polycultures of annual crops – two or more crops simultaneously growing in close proximity. Farmers can also let some flowering weeds reach tolerable levels or use cover crops under orchards and vineyards.

Numerous researchers have shown that increasing plant – and thereby habitat – diversity favors the abundance and effectiveness of natural enemies. For example in cotton fields strip-cropped with alfalfa or sorghum, intensified populations of natural enemies have substantially decreased plant bugs and moth and butterfly pests. Beneficials reduced pest insects below economic threshold levels in Georgia cotton that was relay-cropped with crimson clover, eliminating the need for insecticides. In Canadian apple orchards, four to eighteen times as many pests were parasitized when wildflowers were numerous compared to when they were few. In this research, wild parsnip, wild carrot and buttercup proved essential to a number of parasitoids. In California organic vineyards, the general predators and *Anagrus* leafhopper egg parasites that control grape leafhoppers and thrips thrive in the presence of buckwheat and sunflowers. When these summer-blooming cover crops flower early, they allow populations of beneficials to surge ahead of those of pests. When they keep flowering throughout the growing season, they provide constant supplies of pollen, nectar and alternative prey. Mowing every other row of cover crops – an occasionally necessary practice – forces these beneficials out of the resource-rich cover crops and into vines.

In polycultures, apart from the evident increase in plant species diversity, there are changes in plant density and height, and therefore in vertical diversity. All these changes affect density of pests and other organisms. The combination of tall and short crops can also affect dispersal of insects within a cropping system. For example, in Cuba farmers grow strips of corn or sorghum every ten meters within vegetables or beans in order to provide physical barriers to reduce the dispersion of thrips (*Thrips palmi*).

In China, researchers working with farmers in ten townships in Yumman, China, covering an area of 5350 hectares, encouraged farmers to switch from rice monocultures to planting variety mixtures of local tall rice with shorter hybrids. Tall plants provided a barrier for inoculum dispersal, but in addition enhanced genetic diversity reduced blast incidence by ninety-four percent and increased total yields by eighty-nine percent. By the end of two years, it was concluded that fungicides were no longer required.

Managing vegetation surrounding the field

Hedgerows and other vegetation in field margins can serve as reservoirs for natural enemies. These habitats can be important overwintering sites for the predators of crop pests. They can also provide natural enemies with additional pollen, nectar and other resources.

Many studies have shown that beneficial arthropods do indeed move into crops from field margins, and biological control is usually more intensive in crop rows near wild vegetation than in field centers:

- In Germany, parasitism of the rape pollen beetle is about 50 percent greater at the edges of fields than in the middle.
- In Michigan, European corn borers at the outskirts of fields are more prone to parasitism by the ichneumonid wasp *Eriborus terebrans*.
- In Hawaiian sugar cane, nectar-bearing plants in field margins improve the numbers and efficiency of the sugar cane weevil parasite *Lixophaga sphenophori*.

Practical management strategies arise from understanding these relationships. A classical example comes from California, where the egg parasite *Anagrus epos* controls the grape leafhopper in vineyards adjacent to French prunes. The prunes harbor an economically insignificant leafhopper whose eggs provide *Anagrus* with its only winter food and shelter.

Creating corridors for natural enemies

Sowing diverse flowering plants into strips that cut across fields every 165 to 330 feet (50–100 meters) can provide natural enemies with highways of habitat. Beneficials can use these corridors to circulate and disperse into field centers.

European studies have confirmed that this practice increases the diversity and abundance of natural enemies. When sugar beet fields were drilled with corridors of tansy leaf (*Phacelia tanacetifolia*) every twenty to thirty rows, destruction of bean aphids by syrphids intensified. Similarly, strips of buckwheat and tansy leaf in Swiss cabbage fields increased populations of a small parasitic wasp that attacks the cabbage aphid. Because of its long summer flowering period, tansy leaf has also been used as a pollen source to boost syrphid populations in cereal fields. On large organic farms in California, strips of *Alyssum* are commonly planted every fifty to one hundred meters within lettuce and cruciferous crop fields to attract syrphid flies that control aphids.

Some grass species can be important for natural enemies. For example, they can provide temperature-moderating overwintering habitats for predaceous ground beetles. In England, researchers established "beetle banks" by sowing earth ridges with orchard grass at the centers of cereal fields. Recreating the qualities of field boundaries that favor high densities of overwintering predators, these banks particularly boosted populations of *Dometrias atricapillus* and *Tachyporus hypnorum,* two important cereal aphid predators. A 1994 study found that the natural enemies the beetle banks harbored were so cost-effective in preventing cereal aphid outbreaks that pesticide savings outweighed the labor and seed costs required to establish them. The ridges can be 1.3 feet high, 5 feet wide and 950 feet long (0.4 meters by 1.5 meters by 290 meters).

For more extended effects, it is recommended to plant corridors with longer-flowering shrubs. In northern California, researchers connected a riparian forest with the center of a large monoculture vineyard using a vegetational corridor of sixty plant species. This corridor, which included many woody and herbaceous perennials, bloomed throughout the growing season, furnishing natural enemies with a constant supply of alternative foods and breaking their strict dependence on grape-eating pests. A complex of predators entered the vineyard sooner, circulating continuously and thoroughly through the vines. The subsequent food-chain interactions enriched populations of natural enemies and curbed numbers of leafhoppers and thrips. These impacts were measured on vines as far as one hundred to one hundred fity feet (thirty to forty-five meters) from the corridor.

Selecting the right flowers

When choosing flowering plants to attract beneficial insects, note the size and shape of the blossoms. That's what dictates which insects will be able to access the flowers' pollen and nectar. For most beneficials, including parasitic wasps, the most helpful blossoms are small and relatively open. Plants from the aster, carrot and buckwheat families are especially useful. (See Table 1 on pages 35–36).

It should also be noted when the flower produces pollen and nectar: timing is as important to natural enemies as blossom size and shape. Many beneficial insects are active only as adults and only for discrete periods during the growing season: they need pollen and nectar during these active times, particularly in the early season when prey are scarce. One of the easiest ways farmers can help is to provide them with mixtures of plants with relatively long, overlapping bloom times.

Current knowledge of which plants are the most useful sources of pollen, nectar, habitat and other critical needs is far from complete. Clearly, many plants encourage natural enemies, but scientists have much more to learn about which plants are associated with which beneficials, and how and when to make desirable plants available to target organisms. Because beneficial interactions are site-specific, geographic location and overall farm management are

critical variables. In lieu of universal recommendations, which are impossible to make, farmers can discover many answers by investigating the usefulness of alternative flowering plants on their farms.

Enhancing biodiversity – checklist for farmers:

- Diversify enterprises by including more species of crops and livestock.
- Use legume-based crop rotations and mixed pastures.
- Intercrop or strip-crop annual crops where feasible.
- Mix varieties of the same crop.
- Use varieties that carry many genes – rather than just one or two – for tolerating the same disease.
- Emphasize open-pollinated crops over hybrids for their adaptability to local environments and greater genetic diversity.
- Grow cover crops in orchards, vineyards and crop fields.
- Leave strips of wild vegetation at field edges.
- Provide corridors for wildlife and beneficial insects.
- Practice agroforestry; where possible, combine trees or shrubs with crops or livestock to improve habitat continuity for natural enemies.
- Plant microclimate-modifying trees and native plants as windbreaks or hedgerows.
- Provide a source of water for birds and insects.
- Leave areas of the farm untouched as habitat for plant and animal diversity.

Designing a habitat-management strategy

To design an effective plan for successful habitat management, first gather as much information as you can. Make a list of the most economically important pests on your farm. For each pest, try to find out:

- what are its food and habitat requirements;
- what factors influence its abundance;
- when does it enter the field and from where; what attracts it to the crop;
- how does it develop in the crop and when does it become economically damaging;
- what are its most important predators, parasites and pathogens;
- what are the primary needs of those beneficial organisms;
- where do these beneficials overwinter, when do they appear in the field, where do they come from, what attracts them to the crop, how do they develop in the crop and what keeps them in the field;
- when do the beneficials' critical resources – nectar, pollen, alternative hosts and prey – appear and how long are they available; are alternate food sources accessible nearby and at the right times; which native annuals and perennials can compensate for critical gaps in timing, especially when prey are scarce.

Key information needed in crafting a habitat management plan:

1) ECOLOGY OF PESTS AND BENEFICIALS

- What are the most important (economic) pests that require management?
- What are the most important predators and parasites of the pest?
- What are the primary food sources, habitat, and other ecological requirements of both pests and beneficials? (From where does the pest infest the field, how is it attracted to the crop, and how does it develop in the crop? From where do the beneficials come, how are they attracted to the crop, and how do they develop in the crop?)

2) TIMING

- When do pest populations generally first appear and when do these populations become economically damaging?
- When do the most important predators and parasites of the pest appear?
- When do food sources (nectar, pollen, alternate hosts, and prey) for beneficials first appear? How long do they last?
- What native annuals and perennials can provide such habitat needs?

Rolling out the strategy

This paper presents some ideas and principles for designing and implementing healthy, pest-resilient farming systems. It has been explained why reincorporating complexity and diversity is the first step towards sustainable pest management, and the paper describes the two pillars of agroecosystem health (Figure 4):

- fostering crop habitats that support beneficial fauna
- developing soils rich in organic matter and microbial activity

Well-considered and well-implemented strategies for soil and habitat management lead to diverse and abundant – although not always sufficient – populations of natural enemies.

As farmers develop a healthier, more pest-resilient system for their farms they may ask themselves:

- How can species diversity be increased to improve pest management, compensate for pest damage and make fuller use of resources?
- How can the system's longevity be extended by including woody plants that capture and recirculate nutrients and provide more sustained support for beneficials?
- How can more organic matter be added to activate soil biology, build soil nutrition and improve soil structure?
- Finally, how can the landscape be diversified with mosaics of agroecosystems in different stages of succession and with windbreaks, living fences, etc?

Once farmers have a thorough knowledge of the characteristics and needs of key pests and natural enemies, they are ready to begin designing a habitat-management strategy specific for their farm. *Choose plants that offer multiple benefits* – for example, ones that improve soil fertility, weed suppression and pest regulation – and that don't disrupt desirable farming practices. *Avoid potential conflicts:* in California, planting blackberries around vineyards boosts populations of grape leafhopper parasites but can also exacerbate populations of the blue-green sharpshooter that spreads the vinekilling Pierce's disease. In placing selected plants over space and time, *use the scale – field- or landscape-level – that is most consistent with intended results.* And, finally, *keep it simple:* the plan should be easy and inexpensive to implement and maintain, and should be easy to modify as needs change or results warrant change.

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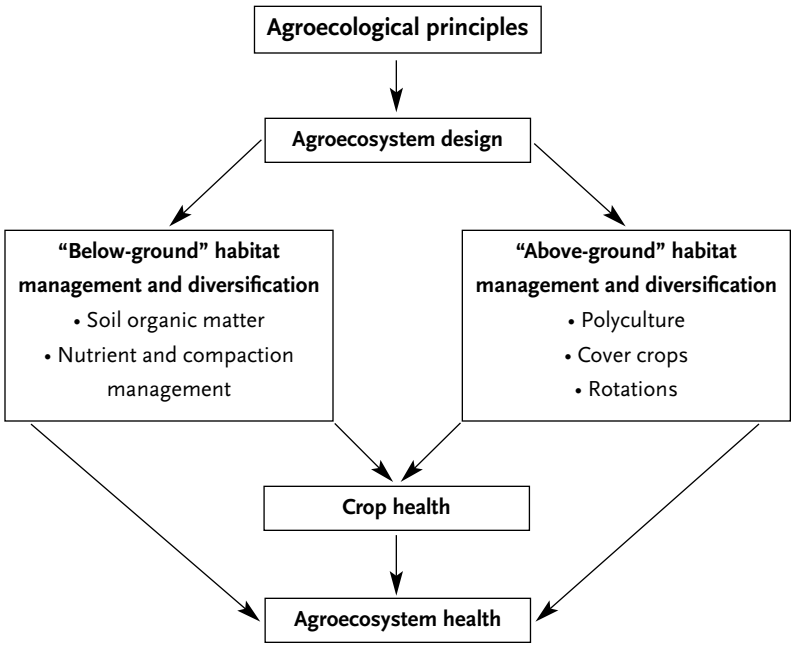
Figure 4. Pillars of agroecosystems health



Guidelines for designing healthy and pest-resilient farming systems

- Increase species in time and space with crop rotations, polycultures, agroforestry and crop-livestock systems.
- Expand genetic diversity with variety mixtures, multilines and local germplasm.
- Conserve or introduce natural enemies and antagonists with habitat enhancement or augmentative releases.
- Boost soil biotic activity and improve soil structure with regular applications of organic matter.
- Enhance nutrient recycling with legumes and livestock.
- Maintain vegetative cover with reduced tillage, cover crops or mulches.
- Enhance landscape diversity with biological corridors, vegetationally diverse crop-field boundaries or mosaics of agroecosystems.

Table 1. Plants that attract beneficial insects

spider	many insects	Caraway, dill, fennel, cosmos, marigold, spearmint
spider mite destroyer	spider mite	Carrot family (goldenrod, yarrow), bishop's weed; maintain permanent plantings
Syrphid fly (hover flies) (*Syrphidae* family)	aphid	Carrot family (Queen Anne's lace, dill, fennel, caraway, tansy, parsley, coriander, bishop's weed), the sunflower family (*coreopsis,* Gloriosa daisy, yarrow, cosmos, sunflower), marigolds, candytuft, sweet alyssum, *ceanothus,* holly-leaved cherry *(Prunus ilicifolia),* buckwheat, scabiosa, spearmint, coyote brush *(Baccharis pilulari),* knotweed *(Polygonum aviculare),* California lilacs *(Ceanothus spp.),* soapbark tree, meadow foam *(Linnanthes douglasii),* baby-blue-eyes *(Nemophila)*
Tachinid fly *(Tachinidae* family)	cutworm, armyworm, tent caterpillar, cabbage lopper, gypsy moth, some attack sawfly, Japanese beetle, May beetle, squash bug, green stink bug, sowbug	Carrot family (caraway, bishop's weed, coriander, dill, parsley, Queen Anne's lace, fennel), goldenrod, sweet clover, *Phacelia spp.,* sweet alyssum, buckwheat, amaranth, buckthorn, *Heteromeles arbutifolia*
Tiger beetle (*Cicindelidae* family)	many insects	Maintain permanent plantings and some exposed dirt or sand areas
Minute Pirate Bug (*Anthocoridae* family), (*Orius* spp)	Thrips, spider mite, leafhopper, corn earworm, small caterpillars, many other insects	Effective predators of corn earworm eggs. Carrot family (Queen Anne's lace, tansy, coriander, bishop's weed, chervil), sunflower family (cosmos, tidy tips *(Layia),* goldenrod, daisies, yarrow), baby-blue-eyes *(Nemophila),* hairy vetch, alfalfa, corn, crimson clover, buckwheat, blue elderberry *(Sambucus caerulea),* willows, shrubs. Maintain permanent plantings or hedgerows.
Parasitic nematodes	Nematodes	Marigolds, chrysanthemum, gaillardia, helenium, *Eriophyllus lanatum,* horseweed *(Conyza canadensis),* hairy indigo, castor bean, *Crotalaria* spp., *Desmodium* spp., sesbania, Mexican tea *(Chenopodium ambrosioides),* shattercane *(Sorghum bicolor),* lupines, *Phaseolus atropurpurens*
Praying mantis (*Mantis* spp)	Any insect	Cosmos, brambles. Protect native species by avoiding pesticides.
Predatory mites (*Typhlodromus* spp)	Spider mite	There are many species of predatory mites with ecological requirements, especially with respect to humidity and temperature, that are particular to the species. Avoid use of insecticides. Provide beneficial refugia for non-crop habitat of non-crop mite prey.
Predatory thrips (*Thripidae* family)	Spider mites, aphid, other thrips, Oriental fruit moth, codling moth, bud moth, peach twig borer, alfalfa weevil, whitefly, leafminer, scale	There are several types of predatory thrips. Predatory thrips populations may be conserved/maintained by having non-crop populations of plant-feeding mites (e.g. European red mite, two-spotted spider mite), scales, aphids, moth eggs, leafhoppers and other thrips.
Rove beetle (*Staphylinidae* family)	Aphid, springtail, nematodes, flies; some are parasitic on cabbage-root maggot	Permanent plantings; interplant strips of rye, grains, and cover crops; mulch beds; make stone or plant walkways in garden to provide refuges.
Aphid midge *(Aphidoletes aphidimyza)* (Larvae are aphid predators)	Aphid	Dill, mustard, thyme, sweet clover. Shelter garden from strong winds; provide water in a pan filled with gravel.
Aphid parasites (*Aphidius matricariae* and others)	Aphid	Nectar-rich plants with small flowers (anise, caraway, dill, parsley, mustard family, white clover, Queen Anne's lace, yarrow)
Assassin bug (*Reduviidae* family)	Many insects, including flies, tomato hormworm, large caterpillars	Permanent plantings for shelter (e.g., hedgerows)

Table 1. Plants that attract beneficial insects, continued

Big-eyed bugs (*Geocoris* spp) (*Lyagaidae* family)	Many insects, including other bugs, flea beetles, spider mites, insect eggs and small caterpillars. Will also eat seeds.	Can build up in cool-season cover crops such a berseem clover *(Trifolium alexandrium)* and subterranean clovers (*Trifolium subterraneum)*. Can be found on common knotweed *(Polygonum aviculare)*.
Braconid wasp (*Braconidae* family)	Armyworm, cabbage worm, codling moth, gypsy moth, European corn borer, beetle larvae, flies, aphid, caterpillars, other insects	Nectar plants with small flowers (caraway, dill, parsley Queen Anne's lace, fennel, mustard, white clover, tansy, yarrow), sunflower, hairy vetch, buckwheat, cowpea, common knotweed, crocuses, spearmint)
Damsel bug (*Nabidae* family)	Aphid, thrips, leafhoppers, treehopper, small caterpillars	Anything in the sunflower family (incuding goldenrod, yarrow), alfalfa.
Ground beetle (*Carabidae* family)	Slug, snail, cutworm, cabbage-root maggot; some prey on Colorado potato beetle, gypsy moth and tent caterpillar	Permanent plantings, amaranth; white clover in orchards, mulching.
Lacewing (*Neuroptera* family) (*Chrysoperla and Chrysopa* spp)	Soft-bodied insects including aphid, thrips, mealybug, scale, caterpillars, mite	Carrot family (caraway, Queen Anne's lace, tansy, dill, angelica), sunflower family (coreopsis, cosmos, sunflowers, dandelion, goldenrod), buckwheat, corn, hollyleaf cherry *(Prunus ilicifolia),* flowering bottle tree *(Brachychiton populneum),* soapbark tree *(Quillaja saponaria).* Provide water during dry spells.
Lady beetle or ladybug (*Hippodamia* spp and others) (*Coccinellidae* family)	Aphid, mealybug, spider mite, soft scales	Once aphids leave a crop, lady beetles will also. To retain active lady beetles, maintain cover crops or other hosts of aphids or alternative prey. Carrot family (fennel, angelica, dill, tansy, bishop's weed, Queen Anne's lace), sunflower family (goldenrod, coreopsis, cosmos, golden marguerite (*Anthemis),* dandelion, sunflower, yarrow), crimson clover, hairy vetch, grains and native grasses, butterfly weed *(Asclepias),* black locust, buckwheat, euonymus, rye, hemp sesbania *(Sesbania exaltata),* soapbark tree, buckthorn *(Rhamnus),* saltbush (*Atriplex* spp.), black locust *(Robinia pseudoacacia)*.
Mealybug destroyer *(Cryptolaemus montrouzieri)* (*Coccinellidae* family)	Mealybug	Carrot family (fennel, dill, angelica, tansy), sunflower family (goldenrod, coreopsis, sunflower, yarrow)