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Arthropod Pest Management in Organic Crops

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organic farming, preventative pest management, biological control agents, conservation biological control, organic insecticides

Abstract

Burgeoning consumer interest in organically produced foods has made organic farming one of the fastest growing segments of agriculture. This growth has not been supported adequately by rigorous research to address challenges such as arthropod pest management. The research that has been conducted, however, is complemented by research in aspects of conventional agriculture that may have applicability in organic systems, as well as by research in underpinning fields such as applied ecology. This article synthesizes the available literature in relation to a conceptual model of arthropod pest management strategies suitable for organic systems. The present work uses the four phases of the model to review the strategies in an agroecological context and provides a synthesis of the factors that influence the success of each phase. Rather than constituting a fringe science, pest management research for organic systems draws on cutting edge science in fields such as landscape and chemical ecology and has a bright future.

INTRODUCTION

Organic agriculture has experienced rapid worldwide growth during the last decade. According to recent surveys (162), more than 31 million hectares are currently under organic management in approximately 120 countries. This represents less than 1% of the total agricultural area of these countries. In developed countries, the percentage of organic farmland ranges from 0.01% to 13.5% (led by Austria). In developing countries, the range is 0.01% to 2% (led by Bangladesh). The worldwide market for organic products is estimated at $28 billion (2004 statistics), with the highest growth occurring in the United States, where organic sales grew by $1.5 billion in 2005 to reach $12.2 billion. Recently, organic production of export cash crops of coffee, cocoa, and cotton has increased rapidly in recent years (162). In developed countries, organic fruit and vegetable production has expanded to serve local and export markets (8a, 65a, 103a).

Despite the growth of organic agriculture, there has been a lack of research-based information to address the need for a greater understanding of the mechanisms operating in organic farming systems, including plant-pest interactions. However, there has been increasing interest among the scientific research community in organic systems research. Niggli & Willer (115) discuss the growth of organic research in Europe. In the United States, the total number of organic research acres in the land grant university system more than tripled between 2001 and 2003, with 18 institutions taking the step of certifying their organic research acreage (138).

The underlying principles of arthropod pest management in organic systems involve the adoption of ecologically sound practices specified by international and national organic production standards (35, 81, 150). Emphasis is placed on the use of multiple and varied tactics incorporated into the cropping system design to prevent damaging levels of pests, thus minimizing the need for curative solutions. In his historical perspective on integrated pest management (IPM), Kogan (94) calls attention to early IPM proponents that emphasized ecological approaches to establish more permanent solutions to pest problems. Despite this, reactive approaches have continued to dominate pest management decision-making in conventional agriculture because inorganic/synthetic pesticides cost comparatively little to use, but the price of pesticides does not reflect the risks and social costs associated with their use (19). Nonetheless, IPM has provided a framework for the development of pest management programs in organic systems, i.e., the IPM Continuum, culminating in an approach that emphasizes preventative tactics such as enhancement of natural enemies of pests, cultural methods, and plant resistance (94).

Wyss et al. (165) have proposed a conceptual model for the development of an arthropod pest management program for organic crop production. In this model, indirect, preventative measures are of highest priority to be considered early in the adoption process, followed by more direct and curative measures only when needed (**Figure 1**). The present work uses the four phases of Wyss's model to review arthropod pest management strategies suitable for organic systems. While the focus of this paper is arthropod pest management, organic systems are holistic in nature, so pest management considers all pest taxa including pathogens, weeds, and vertebrates. Our goal is to provide readers with a better understanding of the progress and prospects for arthropod pest management research pertinent to organic farming worldwide, with an emphasis on systems research and, where possible, with examples of research conducted on certified organic land.

FIRST-PHASE STRATEGIES

As defined here, first-phase cultural practices are specific crop production practices implemented in the initial stages of a long-term, organic farm plan to reduce the likelihood of

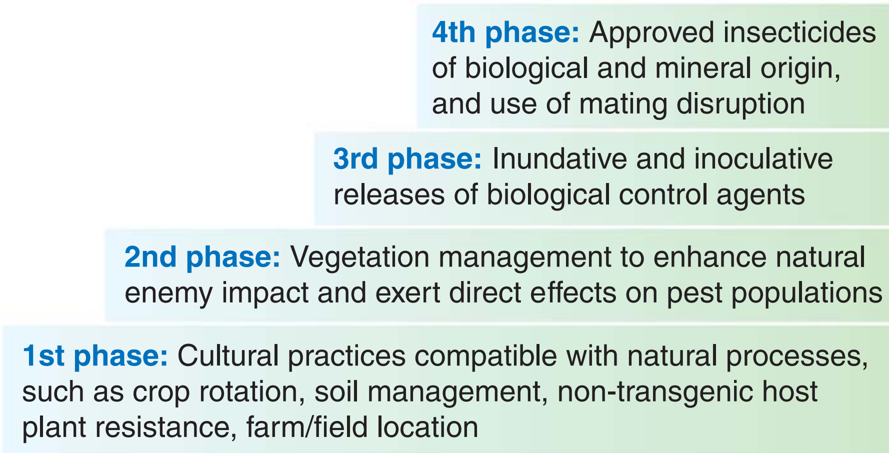

Figure 1

Diagrammatic representation of arthropod pest management strategies for organic crops. Priority is given to preventative strategies, which are considered first, followed by more direct measures if preventative strategies are not sufficient (data from Reference 165).

pest infestation and damage. They are based on the general strategies listed in **Table 1**.

Cultural practices are among the oldest techniques used for pest suppression, and many of the preventative practices used in conventional and organic farming today have their roots in traditional agriculture (113). Because only a limited range of suppressive pest control tactics are available to organic growers, knowledge-intensive cultural practices form the basis of organic pest management programs. The challenge for organic farmers and researchers has been to identify sets of geographically appropriate and crop-specific practices that in combination are effective in preventing economic pest damage. Furthermore, cultural practices may have opposing effects on different pests (64), so selection of specific practices must be based on an overall pest risk assessment. To comply with organic standards, cultural practices that can result in soil erosion and environmental degradation (e.g., excessive tillage, summer fallowing, burning of crop residue) are discouraged but may be allowed under certain circumstances.

Coverage of the broad array of available cultural arthropod control tactics is well

Table 1 General strategies underlying first-phase cultural practices with examples

Strategy	Factors or practices that may be manipulated to prevent or avoid pests
Make the crop unavailable to pests in space and time through knowledge of pest biology	Farm site selection, crop isolation or rotation, manipulate timing of planting or harvest, destroy diapausing pests in soil or in plant residues
Make the crop unacceptable to pests by interfering with oviposition preferences, host plant discrimination, or host location	Intercropping, trap cropping, mulching
Reduce pest survival on crop by enhancing natural enemies	Increase crop ecosystem diversity through habitat manipulation
Alter the crop's susceptibility to pests	Breeding of pest resistant or tolerant cultivars (non GMO), enhancing soil quality and fertility

beyond the scope of this review, and a relatively quick search yields volumes of literature on the subject. Bajwa & Kogan (13) give an excellent overview of the features characterizing cultural controls. The reader is also referred to References 52, 57, 72, and 130 for discussions of cultural control concepts with examples, and to References 134 and 156 for reviews on trap cropping and mechanical control methods, respectively. In this section we provide a review of some other key cultural arthropod management practices commonly used in organic crop production that are best considered in the early stages of farm planning.

Farm Location and Crop Isolation/Rotation

Many factors may influence farm site selection, including climate, topography, soil type, crop history, and economic considerations (12). Data on pest distribution may also be used to facilitate the geographical location of specific crops (84). Although pest management is not always the most important consideration in choice of farm site, many organic farms are located in geographic regions where climatic conditions are unfavorable for pest outbreaks. In some cases a primary pest may be avoided by selecting a site that is ideal for the crop and natural enemies of the pest but unfavorable for the pest itself. For example, a significant portion of organic tree fruit production in the United States is located in regions where insect pests such as the plum curculio, *Conotrachelus nenuphar*, are uncommon or absent (11). At the local level, an organic farmer may have the flexibility to grow a given crop in fields to which it is best suited or to choose a crop species or cultivar best adapted to available growing areas. Landscape factors are also amenable to a degree of manipulation, and these are discussed in the following section on second-phase strategies.

Crop isolation/rotation strategies are most effective against pests that do not disperse over great distances and/or that overwinter in or near host crop fields. Examples include the carrot rust fly (*Psila rosae*) (31), Colorado potato beetle, *Leptinotarsa decemlineata* (161), and onion maggot, *Delia antiqua* (158). In contrast, crop isolation/rotation is much less effective for pests such as the cabbage maggot (*Delia radicum*) that move great distances (32). In such cases, crop rotation on a regional basis may be the only effective approach (70), although this is not usually practical. The isolation of susceptible crops from surrounding host crops can be an effective management strategy for aphid-borne virus diseases, although distances of up to 25 km may be necessary to prevent the spread of virus (135).

While crop rotation with certain cover crops may have beneficial effects associated with reduction of soil pests, diseases, and weeds, consideration must also be given to the potential adverse affects of pest-suppressive rotations on crop yields via competition and/or secondary plant compounds (98), or from secondary pests such as wireworm that may be attracted to the rotational crop (1). Rotation with glucosinolate-containing Brassicaceae can be beneficial through biofumigation effects against some soil-borne pests and diseases (91).

Soil Quality Management

Proponents of organic farming have long promoted the view that the likelihood of pest outbreaks is reduced with organic farming practices, including the establishment and maintenance of "healthy" soil (78, 111, 116). Altieri et al. (5) state that agroecosystem health can be optimized through two pillars: habitat management (see Second-Phase Strategies, below) and soil fertility management. Within this context, organic or ecologically based pest management considers belowground and aboveground habitat management equally important. In organic farming, enhancement of soil fertility is accomplished through rotations, cover cropping, and the application of plant and animal materials (35, 81, 150). Recent studies have shown that plant resistance to insect and disease pests is linked to optimal physical, chemical, and, perhaps most importantly, biological properties of soil (4). Several researchers have reported lower numbers of pest insects on crops grown with organic compared with synthetic sources of fertilizer (9, 25, 40, 54, 86). In paired comparisons of soil from organic and conventional farms, Phelan et al. (120) experimentally partitioned fertilizer source and soil management history effects influencing the European corn borer (ECB), *Ostrinia nubilalis*, host preference for corn. They demonstrated a lower level of ECB oviposition on corn grown in organically managed soil and suggested that the observed pattern of ECB egg laying resulted from a form of biological buffering as a result of organic-soil management. Subsequent experiments supported this mineral balance hypothesis and suggested that the organic matter and microbial activity associated with organically managed soils provide a buffering capability to maintain optimal nutrient and mineral balance in plants, which in turn affects the performance of phytophagous insects (7, 121). Potato grown in manure-amended soils was an inferior host for the Colorado potato beetle compared with potato grown in synthetically fertilized soil (6).

Organic mulches are often used in organic farming to add organic matter to soil and to increase soil-moisture-holding capacity and reduce soil temperature. Studies have shown that application of straw mulch can suppress some insect pests such as the Colorado potato beetle (29, 143, 168), probably through a combination of effects involving reduced host-finding ability and increased predation from natural enemies. Straw mulch has also been well studied in reducing aphid infestation and virus incidence in several crops (50, 129). However, development of some pests such as the squash bug, *Anasa tristis*, and the American palm cixiid, *Myndus crudus*, are favored by application of organic mulch (38, 79).

Tillage Practices

Conservation tillage practices are utilized in organic farming, often combined with cover cropping and mechanical cultivation to control weeds. Conservation tillage is used primarily for soil and water conservation, but tillage can significantly affect arthropod pest and natural enemy abundance and diversity (53, 110). Conservation tillage conditions favor a rich soil biota that can improve nutrient recycling and plant health. Kladivko (92) discusses the effects of tillage practices on soil organisms and concludes that most taxa have greater abundance in conservation tillage than in conventional tillage systems. Holland (76) gives a comprehensive review of the environmental implications of adopting conservation tillage in Europe, including effects on micro-, meso-, and macrofauna. Additional studies demonstrating the benefits of conservation tillage in arthropod pest management are listed in **Table S1** (follow the Supplemental Material link from the Annual Reviews home page at **http://www.annualreviews.org**). In addition to tillage, other mechanical crop management activities (e.g., mechanical weed control and grass cutting) may reduce numbers of generalist arthropod predators, particularly spiders and staphylinid beetles (148).

HPR: host plant resistance

Host Plant Resistance

There are a number of excellent reviews and discussions on the role of host plant resistance (HPR) in arthropod pest management including Kogan (93), Maxwell (109), Smith (136), van Emden (153), Fritz & Simms (60), Bernays & Chapman (22), Eigenbrode & Trumble (55), Gatehouse (63), and Sharma & Ortiz (133). Stout et al. (144) provide a review of the use of elicitors of induced plant resistance in arthropod pest management. Here we compare the utility of HPR for arthropod pest management in conventional and organic farming systems.

Although HPR is considered the foundation of IPM (109), for economic reasons it

Conservation biological control: modification of the environment or existing practices to protect and enhance specific natural enemies or other organisms to reduce the effect of pests

has had limited application for the control of arthropod pests in conventional agriculture. For example, in vegetable production the efficacy of synthetic insecticides combined with limited tolerance for cosmetic damage make insecticide applications more cost-effective than the planting of a pest-resistant or pest-tolerant variety that may have less than optimal production, storage, or marketing qualities. Although much work has been done to integrate HPR with insecticide use in conventional agriculture, there are only a few examples in which treatment thresholds have been developed and validated specifically for resistant varieties (55).

Van Emden (153) has discussed how the benefits of partial plant resistance outweigh those of high-level resistance when used in combination with other control methods. Although the planting of varieties with partial pest resistance or tolerance may not be cost-effective on conventional farms where pesticides are routinely used, in organic farming the selection of varieties with moderate resistance is practical and even preferable to high-level resistance because varieties with partial resistance maintain low-level pest densities that support natural enemy populations (109, 133). The mechanisms involved in interactions between HPR and biological control have been reviewed in this context (145).

As in conventional agriculture, the use of HPR in organic farming is based more on disease resistance than on resistance to arthropod pests. This is because the breeding for HPR to insects has not progressed as rapidly as has been the case for breeding disease-resistant cultivars, and diseases are generally considered more yield limiting on organic farms than are arthropod pests. Arthropod resistance may at times be a primary consideration in cultivar selection on organic farms where management of a key pest(s) has been problematic. However, cultivar selection should be based not only on susceptibility to key disease and arthropod pests, but also on positive and negative interactions with minor pests and natural enemies and in consideration of all the other pest management strategies being implemented. For example, varieties with partial insect resistance can be utilized to greater effect when the asynchrony between plant growth and peak insect development can be exploited through manipulation of planting and harvest dates. Looking toward the future, organic farmers are hopeful that continued public demand for organic produce combined with growth of the organic seed market may provide commercial incentives for seed companies to expand screening programs for arthropod pest resistance.

SECOND-PHASE STRATEGIES

In this section we explore ecological engineering approaches (67): Conservation biological control, intercropping, and trap cropping strategies that can be implemented after the types of structural (first-phase) strategies covered in the preceding section have been deployed. Importantly, second-phase strategies can be applied independently of the first stage to remedy, at least partially, situations in which soil conditions, choice of site, or variety is suboptimal. The second phase can help the process of conversion to organic production by weaning conventional production systems away from synthetic pesticide inputs.

Conservation Biological Control

Many pest populations can be managed by enhancing the efficacy and local abundance of the existing community of natural enemies through modification of the environment or existing practices, a practice known as conservation biological control (15, 56). This practice is appropriate in organic agriculture because there is minimal use of disruptive broad-spectrum pesticides that otherwise may constrain the action of natural enemies (49, 140). The need for synthetic inputs may also be avoided by an enhancement of natural processes, specifically the ecosystem service of biological pest control provided by predators and parasitoids. Plant diversification can help realize the potential of resource-limited natural enemies by satisfying their requirements for food and shelter. In terms of trophic levels, it enhances the top-down action of natural enemies on pests (the enemies hypothesis of Root [127]). This suggests that increased plant diversity can benefit natural enemies by providing them with favorable microclimate (shelter) (77, 146), a source of alternative hosts or prey (108), or a supply of plant-based foods (i.e., nectar and pollen) (157). The potential role of plant-based foods in biological control by predators and parasitoids has only recently become recognized by major reviews (15, 67, 69, 99, 157). Empirical evidence for the utility of conservation biological control strategies is rapidly accumulating (67) and is supported by modeling work (87). Indeed, the positive response of many natural enemies to conservation biological control strategies highlights the generally depauperate ecological communities in farmland.

One successful example is the use of beetle banks. These semi-permanently vegetated raised strips are established across field centers to provide refugia for carabid and staphylinid beetles and spiders (34), as well as for birds and small mammals (147). In the winter, beetle banks harbor more than 1000 predatory invertebrate individuals per square meter (146). Another approach is the cultivation of flowering insectary strips to provide pollen and nectar, which can enhance natural enemy fitness. These provisioned predators and parasitoids show responses such as increased longevity and higher fecundity (82, 101, 124), and the female-based sex ratio of parasitoid offspring may be increased in favor of females (23). Flower strips can also affect the spatial distribution of natural enemies in and around crops (102, 149). Conservation strips that comprise forbs and grasses effectively combine the two preceding concepts, thus increasing rates of predation (59). In addition, the management of weed strips has been advocated in this context for organic crops (114, 166).

Intercropping

Another approach for managing pests involves intercropping with weeds or secondary crops to interfere directly with pests in a bottom-up manner. This approach is reflected in the resource concentration hypothesis, which proposes that concentrated areas of host plants are easier for herbivores to find and colonize (127). The presence of plants distantly related to the crop plant can visually or chemically interfere with specialist herbivores, making the habitat less favorable. Noncrop plants, however, can encourage generalist herbivores that feed on both noncrop and crop plants (8, 131).

Trap Cropping

Trap cropping (134) is a strategy sometimes used in conjunction with pesticides in conventional agriculture (28) that has clear potential in organic systems. It necessitates that the trap crop be more attractive to the pest as either a food source or oviposition site than the main crop. Indeed, the relative attractiveness and size of the trap crop in a landscape are important factors in the arresting of the pest and consequent success of a trap cropping system. Trap cropping varies according to factors such as plant characteristics, the basis of deployment, and the use of combined approaches (134). In particular, the use of combined push-pull trap cropping has proven successful in settings such as east African corn production (89) and is reviewed by Cook & Pickett (37). The potential for trap cropping to work in organic production systems was demonstrated by work in New Zealand, where the density of the southern green stink bug, *Nezara viridula*, was lowered, the timing of their colonization was delayed, and cob damage to transitionally certified organic sweet corn was reduced when black mustard, *Brassica nigra*, was grown around the perimeter of fields (126).

Biodiversity Responses and Effects in Organic Production

The methods described in previous sections have in common an increase in the level of biodiversity within the agricultural production system. Such increases may be at the first or higher trophic levels and in general are likely compatible with and supported by organic agriculture where increases in overall biodiversity are reported (20). Where plant biodiversity is enhanced (61), this may lead directly to reduced pest densities via the resource concentration hypothesis or trap crop effects. Botanical diversity may also enhance the third trophic level (natural enemies of pests) leading to top-down suppression of herbivores.

Enhanced natural enemy abundance has been reported in several studies of organic systems (51, 71, 166). Although not all studies of the effect of organic agriculture on natural enemies are well conducted (20), good evidence has emerged of effects in recent paired farm comparisons. In the case of spider density on European farms, organic agriculture was associated with a 62% increase compared with conventional farms (132). A recent meta-analysis has shown such effects to be robust for species richness and abundance (20) and that abundance of predatory insects, particularly carabid beetles, was increased under organic conditions while pest populations declined.

The magnitude of effects of natural enemies in organic systems has rarely been measured, but in one study of wheat, predator and parasitoid exclusion cages resulted in aphid densities 2.6 to 11.2 times greater than those apparent on uncaged plants (112). More recent work has provided insights into the effects of natural enemies on crop yield and profitability (117). In that work, exclusion studies with epigeal predators of the bird cherry-oat aphid, *Rhopalosiphum padi*, showed that wheat yield losses were reduced by 61% as a result of the action of predators under organic conditions. Generally, however, little work has been done on the economics of natural enemies in organic production systems. One study of mango production in northern Australia investigated the use of the green tree ant, *Oecophylla smaragdina*, with either soft insecticides (as would be allowable under organic production) or conventional insecticides (118). Ants in the trees plus soft insecticide treatment gave an annual profit of AUD$14.50 compared with AUD$8.38 for trees in the alternative treatment.

Limitations of Second-Phase Strategies

Conservation biological control approaches, such as beetle banks and floral strips provide the opportunity to enhance top-down control while conserving important species of invertebrates, vertebrates, and plants. At the same time, bottom-up approaches, including trap cropping and the intercropping for habitat manipulation, can interfere with the colonization, oviposition, and feeding of pests. Apart from a few studies (10, 18, 166), most research on second-phase strategies has been conducted on conventional rather than organic crops. Indeed, apart from a single inconclusive study (119), there is no published research on the comparative effectiveness of second-phase strategies in organic, IPM, and conventional agriculture. Nonetheless, organic agricultural systems are well suited to the use of second-phase methods because natural enemies in conventional crops are generally subject to the disruptive effects of synthetic pesticides (140) and other practices.

THIRD-PHASE STRATEGIES

The Role of Biocontrol Agents in Organic Agriculture

Inundation and inoculation biocontrol strategies, as defined by Eilenberg et al. (56), involve releasing mass-reared live agents into organic crops to control pests for a brief or extended period. These biological control approaches are best implemented after setting in place the types of structural and conservation biocontrol strategies covered in the preceding sections (i.e., first- and second-phase strategies). Along with fourth-phase strategies, inundation and inoculation biocontrol strategies are considered direct regulation measures that are employed when indirect measures implemented during the first two phases are not sufficiently efficacious. However, it cannot be assumed that all commercially available biocontrol agents are appropriate in organic agriculture (139). The International Federation of Organic Agriculture Movements (IFOAM) Basic Standards for Production and Processing for organic production (81) provide criteria for evaluating whether a particular biocontrol agent can be used. IFOAM and other national guidelines for pest management in organic agriculture recommend the use of predators and parasitoids and allow the use of microbial biological control agents (bacteria, viruses, and fungi) but prohibit the use of genetically modified organisms (139). An important aspect that favors the use of some biocontrol agents is their selectivity against single pest species, which distinguishes them from most approved biological- and mineral-based pesticides.

Unlike first- and second-phase strategies that involve advance planning, biocontrol agents give organic farmers and pest control advisors the opportunity to react rapidly when pest populations reach action thresholds. However, only a limited number of research programs have focused on the development of inundation and inoculation biocontrol methods for organic systems. In greenhouse crops, spider mites have been successfully controlled by releasing predatory mites (21, 36), and similarly, whiteflies have been controlled by releasing parasitoid wasps (160). In field-grown crops, parasitoid releases have been effective in the management of lepidopteran pests of vegetables (104, 169), aphids in wheat (112), and leafhoppers in vineyards (41, 42). In addition, releases of mite, coccinellid, and lacewing predators significantly reduced spider mites, aphids, and leafhoppers in perennial crops (41, 42, 58, 88, 167). However, some important insect pests in organic systems such as the cherry fruit flies, *Rhagoletis cerasi* and *R. cingulata*, in sweet cherries or leafhoppers *Erythroneura variabilis* and *E. elegantula* on grape were not adequately controlled by biocontrol agents because of incompatible life histories of the pest and biocontrol agent or disruption to the released agents by resident ant populations, respectively (41, 97).

Entomopathogens such as *Bacillus thuringiensis* or granulosis viruses have been used successfully against a wide range of pests in organic crops, such as lepidopteran species in tree fruits (3, 14, 27, 46), lepidopteran species in soybean (62), and lepidopteran species and the Colorado potato beetle in vegetables (103, 169). In addition, many other biocontrol control agents originally developed for conventional agriculture have since been adapted for use in organic systems, but much of this work has not been published in peer-reviewed journals. **Table 2** lists biological control agents commonly used in organic agriculture [taken from the above-cited papers, databases of organic research (e.g., **http://www.organic-research.com/**, **http://www.orgprints.org/**), and internet advisory and information services (e.g., **http://www.attra.org/**, **http://www.sare.org/**)]. Releases of biocontrol agents commonly result in reduced pest populations, but economic threshold levels remain breached in many instances (42, 88, 104, 160, 167, 169). Nonetheless, organic farmers often accept lower levels of efficacy from biocontrol agents because they are used in combination with other methods, rather than as a stand-alone tactic, to achieve satisfactory pest control.

Classical biocontrol, the release of exotic agents into a new location for the control of an established (usually exotic) pest, has not previously been discussed because it is carried out by agencies at a regional or national scale rather than by farmers. As a result it is not specifically linked to organic agriculture, although it is recognized that classical biological control agents have an important role in

Inundation biocontrol: use of living organisms to control pests when control is achieved exclusively by the released organisms themselves

Inoculation biocontrol: intentional release of a biological control agent with the expectation that it will multiply and control the pest for an extended period, but not permanently

IFOAM: International Federation of Organic Agriculture Movements

Classical biocontrol: intentional introduction of an exotic, usually coevolved, biological control agent for permanent establishment and long-term pest control

Table 2 Biocontrol agents commonly used for the control of insect pests in organic crops[a]

	Area of application			
Biocontrol agent	**Arable crops**	**Perennial crops**	**Vegetable crops**	**Greenhouse crops**
Bacillus thuringiensis subspecies	Colorado potato beetle, lepidopteran pests	Lepidopteran pests	Lepidopteran pests	Lepidopteran pests
Granulosis viruses		Codling moth, summer fruit tortrix		
Entomopathogenic fungi		Cock chafer and other white grubs, fruit flies	Aphids, whiteflies, white grubs,	Aphids, whitefiles
Entomoparasitic nematodes		Weevils, lepidopteran and dipteran pests, crickets	Weevils, grubs, lepidopteran pests, crickets	Sciarid flies, weevils
Insect parasitoids	Aphids, corn borer	Aphids, leafhoppers, lepidopteran pests	Lepidopteran pests	Aphids, whiteflies, leafminer flies
Insect predators	Aphids	Aphids, psyllids, leafhoppers	Aphids	Aphids, whiteflies, thrips, mealybugs, herbivorous bugs, sciarid flies
Insect parasitoids	Aphids, corn borer	Aphids, leafhoppers, lepidopteran pests	Lepidopteran pests	Aphids, whiteflies, leafminer flies

[a]Information collected from references and databases listed in the text (see Third-Phase Strategies).

the control of nonnative pests (44, 80, 151) and therefore contribute indirectly to organic plant protection strategies (139).

History of Inundation and Inoculation Biocontrol

Biocontrol agents have been used for more than 100 years, and their failures, risks, and successes have been extensively reviewed (44, 45, 75, 80, 152). Several landmarks in biocontrol research worldwide have provided organic farmers with effective methods to control insect pests. In the entomopathogen group, the commercial development of *B. thuringiensis* was a breakthrough in the control of various lepidopteran and chrysomelid pests (74, 96), as was the development of granulosis virus against the codling moth, *Cydia pomonella* (65). The development of mass-rearing and release techniques for parasitoids has facilitated management programs for a variety of insect pests (see **Table 2**) in greenhouse and open-field crops (73, 90, 137). Of less commercial importance was the development of entomopathogenic fungi, entomoparasitic nematodes, and insect predators (see **Table 2**). Recently, Stiling & Cornelissen (142) qualitatively and quantitatively reviewed the research on biocontrol. They concluded that most studies were focused on the control of lepidopteran pests and that parasitoids were the most common biocontrol agents used. Moreover, biocontrol agents significantly increased overall pest mortality by 159%, and the addition of two or more biocontrol agents increased pest mortality by an additional 13% compared with single releases. Although debate on the efficacy of inundation biocontrol agents in agricultural pest management is ongoing (33, 33a, 155), their cost of application is generally greater than that for conventional insecticides (33, 110a). In addition, the cost of biocontrol agents varies greatly by country. For example, biocontrol agents are less costly in the United States than in Europe

(39, 155a), and in developing countries the production and purchase of biocontrol agents are often subsidized by governments and foreign aid organizations.

Limitations of Third-Phase Strategies

Organic farmers all over the world use commercially available agents for inundation or inoculation biocontrol that are in most cases pest species-specific and native to the region. In closed-greenhouse systems, organic farmers successfully use nonnative predator and parasitoid species. In organic farming, priority is given to the use of biocontrol agents, with their relatively minor nontarget effects, over the application of broad-spectrum insecticides of botanical or mineral origin. However, because biocontrol agents lack broad-spectrum activity and because of challenges and costs involved with the registration process, only those biocontrol agents with a potential market for large-acreage crops are considered for commercial development. Therefore, many biocontrol agents for less important pests/crops never pass beyond the developmental stage. An example is the identification of an Australian endemic mite, *Typhlodromips montdorensis*, as a potential biological control agent of mite and insect pests of protected cropping including western flower thrips, *Frankliniella occidentalis* (141). Mass-rearing of biocontrol agents is often done by small companies whose employees may have little knowledge of biocontrol agent biology or conditions influencing performance, resulting in suboptimal or inconsistent product quality (155a). However, the quality of mass-reared biocontrol agents has improved owing to more efficient production systems (154).

Although some of the abovementioned factors have limited the utilization of biocontrol agents in conventional farming, organic farmers regularly use biocontrol agents in spite of limitations because they lack the arsenal of synthetic insecticides available to conventional farmers. Critical information is lacking on how to effectively integrate first- and second-phase strategies with inundation and inoculation biological control. For example, it is not clear how effectively conservation biocontrol can be combined with other forms of biocontrol and other organic agricultural practices, but early results are encouraging (33).

FOURTH-PHASE STRATEGIES

Regulation of Insecticides, Pheromones, and Repellents

Fourth-phase strategies include the application of insecticides of biological and mineral origin, pheromones for mating disruption, and repellent agents as physical barriers. In organic agriculture these are used as a last option for the control of pests when all methods used in preceding phases have failed. The criteria for the evaluation of whether these agents can be used in organic agriculture are provided by the IFOAM Basic Standards for Production and Processing (81), which forms the basis of all national regulations (35, 150). The most important criterion is the nonsynthetic origin of these agents. One allowed exception is the use of synthetic pheromones, which may be used for mating disruption in organic agriculture because they are contained in dispensers and therefore do not come into contact with crops.

The criteria for approved substances differ between the national organic standard organizations with respect to impacts on the environment and on human and animal health. For example, the European Union, in contrast with the United States, does not allow the application of tobacco-based products because of human toxicity and side effects on beneficial organisms. However, further restrictions apply at the country level even within the European Union. For example, rotenone, an insecticidal agent, may be applied in E.U. organic agriculture; however, it is not registered in Germany because it is toxic to fish. Other insecticidal agents such as ryania

(*Ryania speciosa*) or sabadilla (*Schoenocaulon officinale*) have not been used as extensively in Europe as in the United States. This trend also applies to spinosad, an environmentally safe insecticidal agent obtained from the bacterium *Saccharopolyspora spinosa* through fermentation. In European countries, spinosad products may be used only if they are obtained directly from microbial production, whereas the United States and Switzerland allow use of the purified toxin. These differences in regulations provide obstacles to international trade and lead to variability in the labeling of organic food.

A broad array of pest-repellent products, including homemade herbal teas, plant extracts, and fermentation products, and industrial clay and rock powder products (e.g., kaolin) are authorized for use in organic agriculture: Nevertheless, the use of homemade products has declined in recent years because of the commercialization of standardized industrial products.

Current Status

The range of insecticidal agents and frequency of use in organic farming vary depending on the crop and the cropping system. For example, although insecticides are rarely used in organic field corn production, they play an important role in organic vegetable, fruit, and wine production, where they are needed for the management of sucking and chewing insects. The most important botanical insecticides used in organic farming are listed in **Table S2** (follow the Supplemental Material link from the Annual Reviews home page at **http://www.annualreviews.org**).

While botanical insecticides such as pyrethrum, rotenone, neem, and plant oils are commonly used in organic farming (83), others such as ryania, nicotine, and sabadilla are used less frequently. In tree fruit production, mineral oils are applied during winter dormancy to kill the overwintering developmental stages of pests. In greenhouse production, insecticides are used sparingly and consist mainly of insecticidal soaps directed against aphids to ensure that beneficial insects, the most commonly used form of pest management in greenhouses, are not harmed. Spinosad is used on a variety of crops to control a number of insect pests (16). In orchards and vineyards, sex pheromones are also used to disrupt mating of various lepidopteran pests. New repellents such as kaolin clay are effective in controlling various insects in different crops and in some cases can even replace insecticide treatments (30, 43, 106, 164). Organic farmers also produce certain plant (e.g., garlic, black pepper, and stinging nettle) and compost extracts to yield teas and washes to control aphids and other insects (107, 125).

Research on Fourth-Phase Strategies for Organic Systems

Insecticides of biological and mineral origin approved for organic systems have been developed and tested on a variety of crops including vegetable, fruit, and vine crops (48, 159, 165). The use of pyrethrin (extract of chrysanthemum) is restricted owing to side effects on many species of beneficial organisms. Azadirachtin preparations (extract of neem kernels) are now replacing pyrethrin to a large extent because of more specific ingestion toxicity effects and low impact on beneficial organisms. In apple and potato production, azadirachtin has been used effectively to control the rosy apple aphid (163) and the Colorado potato beetle (95), respectively. Spinosad is one of the few relatively new insecticidal agents used in organic farming. It has been successfully tested worldwide against a large number of insects on various crops (16, 123). Its limited use in Europe, however, shows that organic farmers are not merely substituting approved insecticides for prohibited materials and that short-term, suppressive tactics are used only as a last resort. New research on the application of quassia extract (bitter wood, *Quassia amara*) for the control of the apple sawfly and woolly apple aphid in fruit production has yet to demonstrate the full potential of all available active ingredients (68).

Recent research on the use of pheromones for mating disruption against various lepidopteran pests in organic fruit, vine, and vegetable crops has focused on the monitoring of damaging insects such as the pea moth, *Cydia nigricana*, the olive fruit fly *Bactrocera oleae*, and the cutworm, *Agrotis* spp. (2, 26, 128). Noninsecticidal repellent agents such as kaolin were recently developed and tested in the United States and Europe to protect organic crops from insect pests (43, 47, 164).

Limitations of Fourth-Phase Strategies

Natural insecticides are generally less stable than synthetic materials and degrade quickly in the environment, meaning that they are also less potent and have shorter residual periods than their synthetic counterparts. Therefore, satisfactory arthropod pest management can be achieved only when insecticide use is integrated with other strategies, such as timing applications to minimize harmful effects on beneficial organisms. Much work is still needed to develop insecticide treatment threshold levels for organic farming systems in which natural enemies are prevalent. One of the major barriers to the commercialization of new, selective insecticides of natural origin is that there generally must be a large marketing base in conventional plant protection to cover the high costs associated with obtaining marketing approval (83). Nonetheless, if the quality and efficacy of natural products such as teas, extracts, and fermentation products could be enhanced by commercial research and development programs, better solutions for typical problems of plant protection in organic farming could be found.

CONCLUSIONS

The classification of arthropod pest management methods into four phases as described in this article stresses the spectrum of approaches ranging from those that operate in a purely preventative manner to curative methods generally withheld as a last resort. However, the integration of methods from various phases is important. Such integration is apparent in the documentation for all organic standards but there is a need to better realize such integration in practice.

IBC: integrated biological control

In practice, first-phase considerations such as where to establish an organic production system may need to consider aspects such as landscape complexity to ensure that sufficient seminatural landscape elements are present to serve as sources of natural enemies that could be attracted by second-phase conservation biological control methods. Second-phase tactics could be used in combination with inoculation and inundation methods to improve the success of the release strategies in an approach dubbed integrated biological control (IBC) (66). For example, the Australian endemic egg parasitoid *Trichogramma carverae* is reared commercially for mass release in vineyards for the control of the light brown apple moth, *Epiphyas postvittana*. The parasitoid's longevity is very short, however, limiting its impact on the target and necessitating accurate monitoring so that releases coincide with the peak in host egg densities. Begum et al. (17, 18) showed that the longevity and fecundity of this natural enemy can be improved by providing it access to nectar-producing plants such as alyssum, *Lobularia maritima*, in organic vineyards. Using a different approach, Lundgren et al. (105) demonstrated that weekly sprays of sucrose (an artificial plant-based food) did not improve rates of egg parasitism by *Trichogramma brassicae* following inundative releases in cabbage, compared with an inundative release only or with untreated control treatments. A particularly exciting prospect for the integration of methods is attract-and-reward, which is currently being tested at Lincoln University in New Zealand. Here, a fourth-phase method, lures containing synthetic herbivore-induced plant volatiles, which attract beneficial insects in the field (85, 122), is combined with a second-phase method, rows of flowering buckwheat planted as understories throughout the vineyard as a food reward for parasitoid wasps (24) in an effort to improve the control of *E. postvittana*. Presumably such lures would be allowable so long as the synthetic material did not contact the crop plants, reflecting the current status of synthetic sex pheromone dispensers.

For an organic farm to achieve adequate levels of natural enemy activity, it would be costly to rely upon inundative or inoculative releases alone. Rather, it is important that sufficient source habitat patches are available for naturally occurring predators and parasitoids, that these are sufficiently close to the areas under production or that corridor features are implemented, and that the crops themselves are made attractive to natural enemies. Leys and short-rotation coppice hedges, for example, have value in increasing the diversity and activity of cereal aphid parasitoids (100). If vegetation is not managed to enhance natural enemy impact, pest management will depend heavily on input substitution using third- and fourth-phase strategies.

The successful integration of methods will need to be informed by future studies that provide a clearer understanding of the effects of scale. A meta-analysis of the effects on biodiversity of organic farming (20) highlighted the importance of this factor. While species richness of predatory insects was generally increased in organic farming, compared with conventional practice this effect was most pronounced in small-scale studies. Studies at the landscape scale, in contrast, showed local farming practice (e.g., organic production) to have only a small effect. For an organic farmer, however, being within a landscape dominated by conventional farms with high pesticide input may be disadvantageous. Such regions likely have low natural enemy densities as a result of broad-spectrum pesticide use and few noncrop refuges.

Future studies of the effects of organic agriculture on natural enemies and pests will need to cover several scales (including the landscape scale) rather than confining to within-field or even paired-field studies. The strong effects of scale and the nature of the landscape setting of a given farm show that organic agriculture is neither a panacea nor a prerequisite for achieving ecologically based pest management.

Finally, the volume of pest management research conducted on organic systems is small compared with the far wider literature on integrated pest management for conventional crops. Accordingly, there is a need for more research to be conducted on certified organic land and investigators may be usefully informed by mining the IPM literature. Although modern synthetic pesticides with narrow-spectrum activity and reduced environmental and human health risks are disallowed in organic agriculture, other biological and cultural methods developed for conventional crops may prove useful.

SUMMARY POINTS

1. Despite the growth of organic agriculture, there has been a lack of research-based information to address the need for a greater understanding of the mechanisms operating in organic systems, including plant-pest interactions.
2. The underlying principles of arthropod pest management in organic systems involve the adoption of ecologically sound practices specified by international and national organic production standards. Of highest priority, indirect, preventative measures should be considered early in the adoption process, followed by more direct and curative measures as required.

3. The optional release of biological control agents gives farmers the ability to react rapidly when pest populations increase. But the limited number of commercially available agents points to the need for research to successfully combine inundation and inoculation biological control agents with other organic pest management practices.
4. Although approved insecticides are used as a last option for the control of pests, they play an important role in organic agriculture, particularly in vegetable, fruit, and wine grape production.
5. Future studies of the effects of organic agriculture on natural enemies and pests are encouraged, particularly those that cover several spatial scales, including that of the landscape, rather than confining to within-field or even paired-field studies.

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