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Chapter 3

Pest Control in Organic Farming

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3.1 INTRODUCTION

Pests and diseases cause important losses and are a major concern for farmers, regardless of the production system adopted. Pests and diseases are the main competitors with humans for agricultural products, particularly when it comes from crops grown under high productivity conditions (Oerke and Dehne, 2004; Oliveira et al., 2014). The damage caused by these crop enemies constitutes a major factor in reducing the productivity of many crops, either in the field (preharvest) or later during storage (post-harvest). An average of 35% of potential crop yield is lost to preharvest pests worldwide and post-harvest losses (transport, preprocessing, storage, processing, packaging, marketing, and plate waste) may achieve another 35% (Oerke, 2006; Molden, 2007; Popp et al., 2012), although these estimates present large fluctuations due to a number of factors related to environmental conditions, the plant species being cultivated, the agricultural practices, farmer socioeconomic conditions, and the level of technology used (Oerke and Dehne, 2004; Oliveira et al., 2014).

The principles of arthropod and pathogen management in organic systems involve the adoption of ecologically sound practices designed to prevent damaging levels and minimize the need for curative solutions. Integrated pest management (IPM) provides a framework for pest control in organic systems, as it emphasizes preventive tactics, such as the enhancement of natural enemies of pests, cultural and biotechnical methods, and plant resistance (Wyss et al., 2005; Zehnder et al., 2007).

In addition, defenders of organic farming claim that plant foods like fruits or vegetables from organic crops are better in promoting human health when compared to those produced using conventional production systems.

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However, this is not universally accepted and many argue that it is premature to say that either organic foods are better in terms of safety or nutritional value (Fernandes et al., 2012). Still, many studies have proven that the amounts of bioactive compounds proven beneficial for the human health, such as, for example, phenolic compounds or vitamins with antioxidant activity, are higher in organic products (Lairon, 2010; Guiné et al., 2010; Petkovsek et al., 2010; You et al., 2011; Crecente-Campo et al., 2012; Fernandes et al., 2012; Letaief et al., 2016; Pinto et al., 2016; Žvikas et al., 2016). On the other hand, organic food, that is free from residues of synthetic pesticides, does not have the negative impacts that conventionally produced foods pose on human health by exceeding acceptable limits for pesticide residues (Zhang et al., 2015; European Food Safety Authority, 2016; Ma et al., 2016; Sumon et al., 2016; Wagner et al., 2016).

Crop protection, based on IPM, is an approach based on the knowledge of biological interactions as well as information on the crop and the surrounding environment, that have long been suggested as the future for sustainable crop production (Morgera et al., 2012; Puech et al., 2014; Sacco et al., 2015). IPM principles may be applied to organic agriculture, ensuring adequate pest and disease control with the restricted use of pesticides that is required for farm produce to meet organic standards (Hillocks, 2002).

The first step in IPM, as in organic farming, is the use of preventive mechanisms—*indirect crop protection' methods*—such as the diversification of crops and crop rotation that reduces pest populations through pest–predator balance (Shiva et al., 2004; Sumon et al., 2016) or the implementation of ecological infrastructures, creating landscape heterogeneity and enhancing natural enemies populations (Garfinkel and Johnson, 2015; Garratt et al., 2011). These practices are particularly relevant to organic farming because, if properly managed, it will help to prevent pest and disease outbreaks from occurring (Brown et al., 2015).

Practices related to soil fertility are also strongly related to pest and disease occurrence, and therefore, a healthy crop is the best defense against pests (Garratt et al., 2011; MOSES, 2012). Soil organisms are essential for the decomposition of organic matter, besides providing other ecosystem services, such as the improvement of soil structure or the promotion of disease suppressiveness. Hence, the long-term effects of organic farming generally result in higher organic matter levels, increased soil biodiversity, and aboveground pest suppression (Quist et al., 2016).

Even with the best management, some pest and disease problems are inevitable. In such occasions, organic farmers may adopt suppressive measures—*direct, or curative, crop protection methods*—including, for example, pheromones, habitat management, biological control, mechanical or physical control, and the use of approved natural pesticides (Zehnder et al., 2007; MOSES, 2012; Scialabra, 2015). The use of natural pesticides (biopesticides) should be minimized and integrated with biological, cultural, or other crop protection methods (Horne, 2007). Although permitted by organic associations, some natural insecticides, such as pyrethrum, can disrupt the long-term control of many pests by killing and reducing resident predators and parasites and limiting biological control (Horne, 2007; Rusch et al., 2015).

Pest control does not necessarily mean to completely destroy the target, because in biological systems all living organisms have a niche and are an unquestionably part of a delicate balance, which should be maintained. Therefore, pest control strategies aim at minimizing the populations of certain agents, but keeping a balance in the ecosystems. In nature every pest or disease has a natural predator or parasite (an organism which feeds or lives on another organism), that truly helps to keep the pest or disease population under control. When an imbalance is established, the pest population can grow uncontrolled and cause major problems. Hence, natural enemies play an important role in limiting the densities of potential pests or diseases (Shiva et al., 2004). In fact, only less than 1% of insect species are pests, and only a few hundred of these constitute a problem in the context of agriculture, and more than 90% of all agricultural pest species are under natural control (DeBach and Rosen, 1991; Shiva et al., 2004).

Organic pest management is strongly based on informed decision-making and careful planning. It includes: monitoring and decision-making based on economic thresholds, promoting preventive crop protection methods (growing the most resistant varieties of crops, enhancing natural enemy populations, improving soil health biodiversity) and adopting curative measures only when no other strategy has resulted, based on the adoption of biological, mechanical, biotechnical methods, or as a last resource on chemical control using biopesticides that are organic-approved. These strategies have been defended as effective in controlling pests, while also promoting a healthy and diverse ecosystem, and rejecting the use of genetically modified organisms (Morgera et al., 2012).

3.2 CONCEPTS

IPM is an ecosystem approach to crop production and protection that combines different management strategies and practices to grow healthy crops and minimize the use of pesticides (natural or biopesticides in the case of organic farming) (FAO, 2012). IPM focuses on long-term prevention of pests or their damage through a combination of techniques such as biological control, habitat manipulation, modification of cultural practices, or use of resistant varieties (Allen and Rajotte, 1990; Barzman et al., 2015). Biopesticides are used only when the risk estimate results indicate, when no other crop protection method is available, and according to the established guidelines, with the goal of removing only the target organism. Pest control methods are selected and applied in a manner that minimizes risks to human health, beneficial and nontarget organisms, and the environment.

The decision-making process is based on an assessment of the intervention necessity, through risk assessment, economic thresholds, or predictive models and considering the balance of risk factors; indirect crop protection measures are privileged, especially, natural conservation, while the other control measures are used only if indispensable, with preference being given to cultural, physical, biological, and biotechnical control and with chemical control being used as a last resource (Amaro, 2003).

When addressing crop pests, diseases, and weeds, four questions should be answered:

1. What is the importance of the pest? Which pest? How much? In IPM, risk assessment is the first step—to assess quantitatively (using different sampling methods) and qualitatively (risk factors) the pest, disease, or weed problem.
2. Is the pest/disease tolerable? The second step should be the analysis of the pest or disease population, comparing it with the economic threshold, by evaluating damage versus control method costs.
3. What to do? Thirdly, one should make a rational choice between all available control methods.
4. When and what to do? Finally, decide what, how, and when to do—the decision-making process.

In IPM, risk assessment (pest identification and monitoring) helps to decide whether management is needed. Correctly identifying the pest or disease is essential to know whether it is likely that it will become a problem, while monitoring means checking for harmful organisms at regular intervals in order to evaluate the population dimension or what damage they have caused (Lapchin and Shtienberg, 1999; Koyshibayev and Muminjanov, 2016). In an ideal world, all farmers would monitor pest populations and use forecasting systems prior to making a decision regarding pest control (Barzman et al., 2015).

At first, it is essential to distinguish key pests, secondary pests, and occasional pests. (1) A key pest is a herbivore (insect, pathogen, or another organism) that is consistently present, and if not properly managed, is likely to exceed the economic thresholds. (2) A secondary pest is a herbivore that is often present but rarely exceeds economic thresholds due to naturally present predation and parasitism. (3) An occasional pest is a herbivore that may cause problems once every few years; and only occurs when environmental conditions strongly favor their development (Brown et al., 2015). So, understanding how environmental conditions affect populations of pest and beneficial arthropods is also important to help making effective management decisions.

After monitoring and considering information about the pest, its biology, and environmental factors, one should decide whether the pest can be tolerated or whether it is a problem that warrants control. If control is needed, this collected information will also help to select the most effective management methods and the best time to use them.

This decision is based on the use of economic thresholds: the pest or disease density at which management action should be taken to prevent an increasing pest population from reaching the economic injury level. In many cases, thresholds have not been established, especially for weeds and several pathogens (Koul and Cuperus, 2007; Naylor, 2008; Horsfall, 2012).

3.2.1 Risk Assessment

The importance of the pest is determined by assessing quantitatively pests and diseases (intensity of attack) and analyzing the effect of possible factors that might increase/decrease the damages (risk factors). When addressing pests and diseases it is important to know what they do (symptoms and damage), what they eat (leafs, flowers, stems, fruits), and where they are (plant organ, soil, etc.).

Several sampling methods are used in quantitative risk estimation, but also to assess risk periods, depending on the pest/disease and crop (Hutchins, 1993; Amaro, 2003; Deutscher et al., 2003; Muegge and Robinson, 2011). These methods can be: (1) direct: numerical data are collected from direct observation of a defined number of plant organs—visual observation; or (2) indirect: capture of pest insects and natural enemies through appropriate devices—sweep nets, aspiration, traps, corrugated cardboard strips, pit-falls.

The sampling methods should be applied randomly in alternate pathways in the field. The adopted methods should be simple, accurate, low-cost, time-efficient, and reliable (Pedigo and Buntin, 1993; Rodrigues et al., 2004).

Visual observation involves in situ direct counting of arthropods or disease symptoms on a pre-established number of units (stems, leaves, flowers, fruits, plants) in a sample (Hutchins, 1993). It must be representative of the parcel of land or homogeneous cultural unit. For example, for the grapevine moth, *Lobesia botrana*, wine growers must observe 200 grapevine clusters in the first and second generations, looking for moth "nests" (Alves, 2007). For cotton whitefly infestations, the whiteflies and their damage should be observed while scouting the field and the degree or percentage of infestation recorded (Monks et al., 2012). One should also search for and quantify the presence of natural enemies, such as predators or larvae and adult parasitoids.

Another monitoring technique consists of using a specific collection device (sweep, beating-tray, polyethylene sheet) along several selected branches and collecting the arthropods dislodged from the impact of a blunt object—the *knockdown technique* (Hutchins, 1993). The material is then observed and counted in the laboratory. This technique is suitable to collect relatively immobile species or stages of arthropods. For example, to assess the populations of the woolly apple aphid, *Eriosoma lanigerum*, the observer should perform one quick whack at one side of 25 trees in blocks with a history of infestation (Fig. 3.1) (Simone, 2004). Farmers should also search for and quantify the presence of natural enemies.

Arthropods that are somewhat mobile once dislodged are candidates for sampling techniques using sucking apparatus (Hutchins, 1993). *Aspiration* is an indirect method with low selectivity that obliges sorting for target species prior to counting.

Risk assessment also uses different *trapping techniques* (Amaro, 2003; Yi et al., 2012). Several variations of traps have been developed as a means of capturing and holding arthropods: (1) interception traps—devices that capture insects accidentally, that are rather selective, and (2) attraction traps—devices that capture insects based on their responses to different stimuli (light, color, food, or mating) and that are more or less selective (Fig. 3.2). The traps provide information about species forthcoming, life cycle, population density, or distribution in the field.

Some of the most common traps are sticky traps that attract flying insects by color. *Visual traps* include attraction with short-wavelength light (e.g., blacklights) known to generally attract flying arthropods (Hutchins, 1993). Other traps combine color attraction with food stimulus (easy or Tephri traps) or using sex pheromones to attract insects based on their reproduction or mating instinct. These last traps are very specific and simplify insect counting.

FIGURE 3.1 Knockdown techniques in (A) olive trees and (B) weeds.

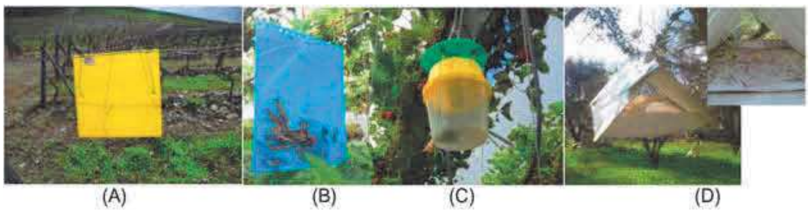

FIGURE 3.2 Attraction traps—devices that capture insects based on their responses to different stimuli: (A, B) color, (C) food/color, or (D) mating (delta trap with sexual pheromone).

A *band of corrugated cardboard* or other material placed on the lower trunk of a tree or plant can be used to capture larvae searching for pupation sites (Jumean et al., 2005). This method is used for the codling moth, *Cydia pomonella*, by placing corrugated cardboard bands to capture caterpillars while searching for a place to pupate, counting the number of cocooned insects, and placing them in an insectary or posture sleeve to determine the first adult, the first eggs, and the hatch time.

To monitor soil arthropods or other animals with terrestrial habits, plastic (or other material) containers—*pit-falls*—can be buried at ground level containing a liquid (detergent, alcohol, or formaldehyde) that will kill and store the captured arthropods. The arthropods or other animals are then stored and identified in the laboratory (Hutchins, 1993; Yi et al., 2012).

The biological activity of the soil can also be monitored by assessing the feeding activity and its vertical distribution in situ (Filzek et al., 2004; Römbke, 2014). Plastic strips, called *bait-laminas*, with 16 wells filled with organic material of which the fauna of the soil is fed, are inserted in the soil. The portion of food consumed is proportional to the biological activity of the soil. The soil fauna activity is determined based on the number of holes that are empty after 14 days. This method is internationally standardized.

3.2.2 Risk Factors and Periods

Quantitative pest and disease risk assessment should always go along with an assessment of the factors that might influence the pest or disease and risk periods—qualitative risk estimate of pests and diseases (Sileshi et al., 2007). *Risk factors* are variable and can influence, positively or negatively, the evolution of populations of pests and diseases, such as crop history, abiotic factors (humidity, temperature), biotic factors (presence of natural enemies, existence of alternative shelter or food), cultural factors (cover crops, crop density, soil fertility), and technical and economic factors (pest control measures used, harvest value, market standards, etc.).

Risk periods might be defined as the time period when the probability of population levels above the economic thresholds are higher along the crop cycle. For instance, for barley mildew the high-risk period is when there is a high risk of large number of spores being released in barley crops and the criteria for high-risk periods are day temperature above 15.6º C, dew point deficit (at 09.00) above 5º C, day rainfall below 1 mm, and wind velocity above 246 km (Jones, 2013). The risk periods are specific for each binomial pest/crop or disease/crop, as they are affected by both rate developments.

As the quantitative estimation of risk is very demanding in time, it should be restricted only to the risk periods.

3.2.3 Forecasting Models

Mathematical models, based on environmental conditions that are directly related to the characteristics and development of the pest/disease and on abiotic factors that may influence them positively or negatively, can be used to predict the risk of an insect or disease (Way and van Emden, 2000). These models are usually used by the advisory services, to warn farmers about pest and disease risks.

For example, for codling moth (*Cydia pomonella*) a degree-day model is used (Murray, 2008). This model uses the accumulated degree-days (one degree day results when the average temperature for a day is one degree over the threshold temperature) from a starting point to help predict adult emergence, which occurs around the cumulative degree-days of 90°C. Egg-laying initiates when twilight temperatures are above 15°C and the relative humidity is less than 65%, usually between 18–22 h (Townsend et al., 1998).

Several other pests—*Hiperica postica, Agrostis ipsilon, Delia radicum, Leptinotarsa decemlineata, Delia antiqua, Striacosta albicosta, Ostrinia nubilalis, Quadraspidiotus perniciosus, Bactrocera oleae, Saissetia oleae*—and diseases—*Plasmopara viticola*, *Puccinia hordei, Phytophthora infestans, Erysiphe necator, Septoria nodurum*, among many others—may be predicted using forecasting models that have been tested worldwide (Townsend et al., 1998; Herms, 2013; Jones, 2013).

3.2.4 Economic Thresholds

To answer the question of whether the pest/disease level is acceptable, organic farmers should compare the risk estimates with the economic thresholds—the density of a pest or disease at which a control treatment will provide an economic return (Amaro, 2003). An economic threshold is the insect or pathogen population level or extent of crop damage at which the value of the crop destroyed exceeds the cost of controlling the pest (Fig. 3.3).

It is understood that injury is any observable deviation from the normal (healthy) crop and damage is the decrease in quantity (yield loss) and/or quality of a crop output (Savary et al., 2006). For an adequate decision-making process, risk factors—environmental, technical, or economic (factors that influence the cost of intervention)—need to be considered as they might modify the balance between damages and costs.

Economic thresholds can change throughout the season at different stages of crop development, can vary from variety to variety, and must be constantly revised to account for new pests, new varieties, new management practices, productivity, new marketing standards, and variations in commodity prices. Some examples of economic thresholds are:

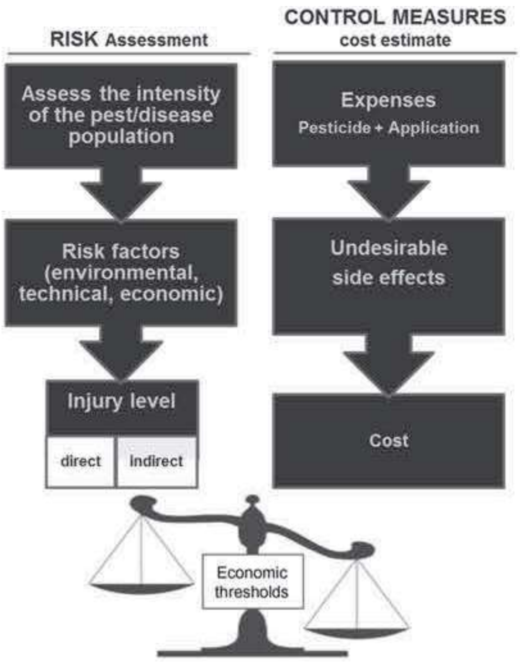

FIGURE 3.3 Economic thresholds—a balance between pest, disease, or weed intensity and the cost of the control methods to adopt, considering the risk factors at stake.

- Bean leaf beetles (*Ceratoma trifurcata*) in soybeans: when defoliation reaches 30 percent (before bloom) and there are five or more beetles per plant;
- Black cutworms (*Agrotis ipsilon*) in corn: when 3 percent or more of the plants are cut and the larvae are still present;
- Leaf miners (*Liriomyza* spp.) in melons: when an average of 15–20 unparasitized larvae per leaf are found (Hernández et al., 2011).

Economic thresholds may not be perfect, but they can help to avoid expensive mistakes. Pest managers cannot afford to take a pest management action without knowing if it is economically sound. Treating a pest needlessly will also induce environmental and social costs, especially when using chemical control, even if based on biopesticide use (e.g., water resources contamination, health costs for workers, etc.).

Management decisions should constantly balance between the costs and benefits of implementing a practice, such as the product cost (for example, a biocontrol agent), fuel (to operate the equipment), labor (to operate the equipment and evaluate treatment efficacy), and sometimes the increase in damage from secondary pests.

A monitoring and risk assessment plan can be designed following the next steps (Godinho, 2015):

1. Draw up a chronological map of crop pests and diseases and natural enemies based on previous years or on the basis of information available if starting an activity.
2. Assign the key enemy status when losses have occurred and it is known that it is likely that an intervention to reduce the attack is needed.
3. Visit your crop periodically and define a proper methodology to estimate pests, diseases, and natural enemies attack.
4. Record the occurrence (presence of individuals or symptoms, presence of natural enemies) in a sheet prepared for this purpose.
5. Diagnose the cause from the symptoms and identify the pests and diseases and natural enemies involved.
6. Assign a value that demonstrates the extent of the injury and the distribution on the field and compare it with known economic thresholds.
7. Make a decision: to "act" or "not act."

3.3 PEST CONTROL METHODS

Unbalanced agricultural systems usually generate pest and disease problems. Therefore, optimizing the management system, including measures to ensure healthier crops, or to create less favorable conditions for pests and diseases, is the major challenge in organic farming (Wyss et al., 2005; Eilenberg and Hokkanen, 2007; Forster et al., 2013; Barzman et al., 2015). Thus, the crop protection strategy adopted—integrated pest management—relies on a combination of "*indirect, or preventive, crop protection*" methods. And, if this approach is insufficient, organic farmers may resort to "*direct, or curative, crop protection*" methods—with priority given to consideration of biological and biotechnical methods, and where the use of natural plant protection products (biopesticides) is restricted to a minimum (Peshin and Pimentel, 2014).

Several control methods can be used against pests and diseases, such as regulatory (regulatory measures to control and reduce the dissemination of insects and pathogens), genetic (plant breeding or selection of varieties that are resistant to specific pests and diseases), cultural (cultural practices that alter the environment, the condition of the host, or the behavior of the pest or disease), physical (use of devices, machines, or other physical methods to control pests), biological (use of natural enemies of pests—beneficial insects and disease-causing organisms—and encouraging their development), and biotechnical (use of insect physiological mechanisms or environmental behaviors, that will negatively affect their survival). When none of the previous methods are available for a specific pest or disease, the use of pesticides that are naturally derived (biopesticides) might be an option.

3.3.1 Indirect and Direct Control Methods

All measures that contribute to the dynamic equilibrium of the farm ecosystem— the agroecosystem—are considered *indirect control methods*, either by avoiding colonization by pests and pathogens or regulating the abundance of pests and pathogens at low levels through biological processes (Letourneau, 2006).

The preventive crop protection approach is based on farm ecological processes, where the crop is the host, the crop field and surroundings are the biotic community with specific abiotic conditions, and the pest or pathogen is the factor that invades and disrupts the system (Kristiansen et al., 2006). All knowledge about plants, pests, and disease ecology benefits the choice of effective preventive crop protection measures.

Preventive measures include the use of resistant varieties and appropriate cultural practices, such as choosing the best planting date and sowing density, reducing the use of nitrogen fertilizers, or maintaining or establishing ecological infrastructures that will protect and enhance the activity of key antagonists (Boller et al., 2004; Letourneau, 2006; Waibel, 2012). Sometimes, the adoption of such measures is difficult: for example, in rice cultivation, planting dates depend on the availability of irrigation water (Waibel, 2012; Strand, 2013).

When a pest or pathogen is established in the crop, and threatens to reduce yields, *direct control methods* need to be considered. Options for curative control methods allowed under organic agriculture guidelines are limited and vary from country to country (Letourneau, 2006). Methods or products for which there is a doubt about negative effects cannot be used.

Direct plant protection control includes biological, biotechnical (e.g. mating disruption), physical, and a restrictive list of highly selective chemical (natural) control procedures (Boller et al., 2004).

Some authors have proposed a conceptual model for arthropod pest management in organic agriculture (Wyss et al., 2005; Forster et al., 2013). This model (Fig. 3.4) establishes a multilevel approach with the highest priority on indirect preventive plant protection measures to be considered early in the adoption process (steps 1 to 3), followed by more direct and curative measures only when needed (steps 4 and 5). This strategy combines different options in farm management and cropping design to limit pest populations below damaging levels, minimizing the need for direct intervention.

3.3.2 Control Methods

3.3.2.1 Legislation

Several regulatory measures to control and reduce the dissemination of insects and pathogens are implemented at national and international levels. As people and commodities move around the world, organisms that present

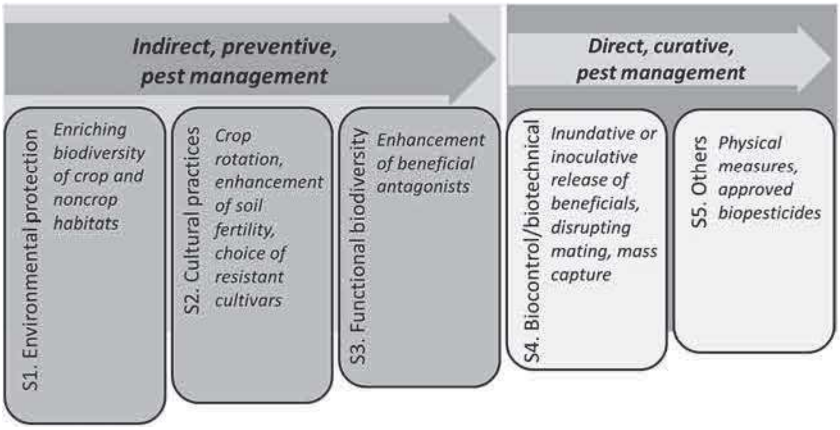

FIGURE 3.4 Five-step approach to pest control in organic agriculture. *Adapted from Wyss et al. (2005), Zehnder et al. (2007).*

risks to plants travel with them. To prevent this dissemination, an international plant health agreement—The International Plant Protection Convention (IPPC)—was established in 1951, aimed at protecting cultivated and wild plants by preventing the introduction and spread of pests.

By protecting plant resources from pests and diseases, the IPPC helps to protect farmers from economically devastating pest outbreaks, the environment from loss of species diversity or of viability and function as a result of pest invasions, the industry from the costs of pest control or eradication, and livelihoods and food security by preventing the entry and spread of new pests of plants into a country, while facilitating world trade through standards that regulate the safe movements of plants and plant products (IPPC, 2012).

At a European level, a common directive on plant health contributes to sustainable agricultural production (COUNCIL DIRECTIVE 2000/29/EC). This regulation aims to regulate the introduction of plants and plant products from countries outside the EU and the movement of plants and plant products within the EU, and imposes eradication and containment measures in case of outbreaks.

When harmful organisms are detected, the countries should implement emergency control measures. For example, in the EU some harmful organisms originated emergency phytosanitary measures to prevent their introduction: *Anoplophora chinensis* (Decision 2012/138/EC); *Anoplophora glabripennis* (Decision 2015/893/EU); *Epitrix* spp. (Decision 2012/270/EU); *Gibberella circinata* (Decision 2007/433/EC); Pepino mosaic virus (Decision 2004/200/EC); *Phytophthora ramorum* (Decision 2002/757/EC); *Pseudomonas syringae* pv. *actinidae* (Decision 2012/756/EU); *Xylella fastidiosa* (Decision 2015/789 EU).

3.3.2.2 Genetic Control Methods

Varieties which are well adapted to local environmental conditions (temperature, nutrient supply, pests, and disease pressure) grow healthier and stronger against pests and diseases. Thus, the use of resistant and well-adapted varieties in organic farming—genetic control—is one of the most effective ways to control crop pests and diseases (Letourneau, 2006; Scialabra, 2015). Resistance characteristics are the most desired traits to be improved, especially in crops that need very intensive and strict plant protection measures, particularly against diseases, as varietal resistance to pests is more difficult to find (Eibach and Töpfer, 2004; Zehnder et al., 2007; Töpfer et al., 2011).

One of the most referred examples of genetic control is the use of rootstock varieties to enhance European vineyard (*Vitis vinifera*) resistance to phylloxera (*Viteus vitifoliae* (Fitch)), an aphid that caused massive destruction of European vineyards in the mid-19th century (Eibach and Töpfer, 2004). The aphid, originated in North America, was carried across the Atlantic in the late 1850s. Vines can be protected from this pest by grafting them to rootstock varieties derived from other vine species (*Vitis angustifolia*) and resistant hybrids (Töpfer et al., 2011).

Selecting varieties with genetically based resistance traits, based on managing the phenotype, health (toxic or repellent properties) and nutrient concentration to reduce its suitability for pests and pathogens, or managing crop and noncrop vegetation to reduce the concentration of food plants for herbivores, is then a cornerstone of successful crop protection in organic farming (Letourneau, 2006; Zehnder et al., 2007). Together with this collection of crop defense tactics, other plant characteristics can be brought up to overcome crop problems related to soil types (texture, depth, and fertility), chemistry (pH, salinity, lime content), drought and excess water, and yield loss either in the field or in the storage facility, that will contribute positively to the crop ecosystem balance (Bettiga, 2003; Letourneau, 2006).

When selecting cultivars, susceptibility to key diseases and arthropod pests and positive and negative interactions with minor pests and natural enemies, are the main aspects to consider. For instance, the asynchrony between plant growth and peak insect development, may avoid economic damage in the crop, or the use of a variety that has a certain level of pest resistance will allow the organic farmer to maintain low-level pest densities that support natural enemy populations (Zehnder et al., 2007), thus reducing the need for further crop control measures.

It is common practice, among organic growers, to choose fruit varieties that are tolerant or resistant to pests. Apple varieties, such as Ariwa, Delorina, Florina, FloRub, Goldrush, Reanda, Red Devil, Renora, Rewena, Rubinola, and Saturn, are less susceptible or even resistant to the rosy apple aphid (Wyss et al., 2005).

Resistant cultivars are available for many crops, providing resistance against fungi, bacteria, viruses, and nematodes, as well as certain insect pests. Plants have developed a magnificent array of structural, chemical, and protein-based defenses that are able to detect invading organisms and stop them before they are able to cause extensive damage. These defenses may be constitutive (preformed barriers such as tough cell walls, waxy epidermal cuticles, hairy tissues, bark) or inducible (production of toxic chemicals in the foliage, fruits, or seeds, pathogen-degrading enzymes, and deliberate cell suicide) (Letourneau, 2006; Freeman and Beattie, 2008).

For example, leaf toughness (due to cell walls often containing lignin that provides an excellent structural barrier) forms a significant impediment to insect herbivore feeding and pathogen ingression on many crops (Agrios, 2005; Freeman and Beattie, 2008). Monoterpenoids, the primary components of essential oils, function as insect toxins and protection against fungal or bacterial attack. An example is the pyrethrins produced by chrysanthemum plants that act as insect neurotoxins. Many other essential oils that function as insect toxins and are relatively harmless to humans include: spearmint (*Mentha* spp.), basil (*Ocimum* spp.), oregano (*Origanum* spp.), rosemary (*Rosmarinus* spp.), sage (*Salvia* spp.), savory (*Satureja* spp.), thyme (*Thymus* spp.), black pepper (*Piper* spp.), cinnamon (*Cinnamomum* spp.), and bay leaf (*Laurus* spp.) (Freeman and Beattie, 2008).

Phytoalexins, such as medicarpin produced by alfalfa (*Medicago sativa*), are isoflavonoids with antibiotic and antifungal properties that are produced in response to pathogen attack. Another group includes alkaloids, a class of bitter-tasting nitrogenous compounds that are found in many vascular plants, which include caffeine, cocaine, morphine, and nicotine. Caffeine is found in plants such as coffee (*Coffea arabica*), tea (*Camellia sinensis*), and cocoa (*Theobroma cacao*). It is toxic to both insects and fungi (Agrios, 2005).

Plant resistance traits may also work indirectly through their effects on natural enemies. For example, certain maize plants (*Zea mays*), when attacked by caterpillars, release a mix of volatile compounds that attract parasitic wasps. Varieties known to produce these induced odor emissions will facilitate biological control by being particularly attractive to parasitoids (Degen et al., 2004).

However, as the available range of varieties is yet too small to fulfill all agronomic and quality demands and the decision to use a resistant variety is set for the season, several crop aspects and cultural practices should be considered: the probability of invasion and the severity of the pests, the balance of natural enemies, the expected and farmer tolerance to crops losses, the product marketability, but also selective pruning, soil fertility management, and adapted organic fertilization are important tools for lowering the risk of pest attacks (Van Emden, 1966; Wyss et al., 2005; Letourneau, 2006; Costa, 2016).

For example, in terms of soil fertilization, a very high nitrogen (N) plant content may attract or enhance insect populations and predispose to diseases like powdery mildew and rust and, at the same time, refrain a plant parasitic nematode, but if potassium (K) is available in large quantities, the circulation of soluble N in the phloem tissue is reduced and retards aphid fecundity (Van Emden, 1966; Letourneau, 2006; Xu et al., 2012; Keller et al., 2015). In contrast, *Verticillium* wilt risk in cotton is higher when K soil content is low and *Pythium* root rot susceptibility is enhanced with calcium (Ca) shortages (Ahanger et al., 2013)

A huge amount of work is still needed to obtain varieties that show high nutrient use efficiency, optimized root morphology, capacity to establish beneficial plant–microbial interactions that play important roles in nutrient uptake efficiency and disease suppression, namely soilborne and other diseases, that are expected to increase with climate change (Lynch, 2007; Hartmann et al., 2008; Jaggard et al., 2010; Forster et al., 2013).

3.3.2.3 Biological Control

Biological control has been defined many times, but a commonly accepted definition was provided by Eilenberg et al. (2001):

"The use of living organisms to suppress the population density or impact of a specific pest organism, making it less abundant or less damaging than it would otherwise be."

In this way, biological control consists on the human use of a specially chosen living organism (including viruses) to control a particular pest (Flint et al., 1999). This chosen organism might be a predator, parasite, or pathogen, naturally occurring or introduced, that acts as an antagonist and will attack the harmful species (Brodeur, 2012; MOSES, 2012). Biological control of crop pests is considered a promising alternative to the use of pesticides and can effectively help farmers banning or reducing pesticide usage (Puech et al., 2014).

Use of biological control requires a lot of background information about the biology and ecology of the pests. Biological control has rarely resulted in negative environmental effects, but for successful adoption it is necessary to demonstrate that natural enemies are effective at controlling pests and that environmental effects will not occur (van Lenteren et al., 2006).

Biological control has several advantages over other types of control (van Lenteren, 1992; Tóth, 2012). These advantages include: long-term management of the target pest by using self-perpetuating agents; limited side effects; and being directed at only one or a few related pests.

TABLE 3.1 Examples of Predators

Beneficial Insect		Pest/crop Binomial
Order	**Species**	
Coleoptera	*Coccinela septempunctata*	Aphids/citrus
	Cryptolaemus montrozieri	Scale/citrus
	Harmonia axyridis	
	Stethorus puctilum	Acari/several
Heteroptera	*Dicyphus cerasti*	Generalist/vegetables
	Dicyphus tamanini	Generalist/vegetables
	Orius albidipennis	Thrips/vegetables
	Orius laevigatus	
	Orius insidiosus	
	Macrolophus caliginosus	Generalist/vegetables
Neuroptera	*Chrysoperla carnea*	Aphids/ several
Diptera	*Aphidoletes aphidimyza*	

Biological control agents

All organisms, with or without human effort, naturally occurring that suppress pests and diseases. Biological control agents include parasitoids, predators, and pathogens (Alston, 2011; Longe, 2016):

- Predator: an organism that captures and kills a prey to feed immediately; larvae or nymphs are very mobile and the adults can have similar eating habits or eat pollen or nectar;
- Parasitoid: an organism that lives totally or partially inside the host organism (endoparasitoids) or outside the host organism (ectoparasitoids) and causes its death after its development; the adults have a free life and feed on sugary substances or have predatory habits;
- Parasite: an organism that lives at the expense of the host throughout the life cycle and weakens the host, which becomes unable to reproduce and may die prematurely.

Invertebrate *predators* are found among Coleoptera, Neuroptera, Hymenoptera, Diptera, Hemiptera, and Odonata, but more than half of all predators are coleopterans (Table 3.1). The most important families within Coleoptera for biological control are Coccinelidae and Carabidae. Other arthropod natural enemies include predatory mites and spiders.

Adults and immatures are often generalists rather than specialists. They consume a large number of prey (adult or immature) during their lifetime and are generally larger than their prey. Some of the adults feed on pollen, if prey are not available. Invertebrate predators actively capture prey using several different methods. Some mobile predators have good vision, such as ground beetles (Carabidae) and jumping spiders (Salticidae), and they chase their prey. Others with poor vision, use a combination of vision and chemical cues to find their prey.

Some predators used for biological control (Fig. 3.5) include the following:

- *Predatory mites* (Order Acari)—play an important role in orchards (mainly, *Typhlodromus pyri*) and greenhouses (e.g., by feeding on phytophagous mites and thrips) (van Lenteren, 1992; van Maanen et al., 2010);
- *True bugs* (Order Hemiptera)—general feeder (e.g., *Orius* spp.), both immatures and adults eating eggs, immatures, and adults of a diversity of insects and mites (Dissevelt et al., 1995; Tommasini et al., 1997; Andorno and López, 2014; Cruz-Rodríguez et al., 2016);
- *Lady beetles* (Order Coleoptera, family Coccinelidae)—adults and larvae feed on soft-bodied prey, mainly aphids but also whiteflies, mites, mealybugs, and scale insects (Obrycki and Kring, 1998; Obrycki et al., 2009; Michaud, 2012);

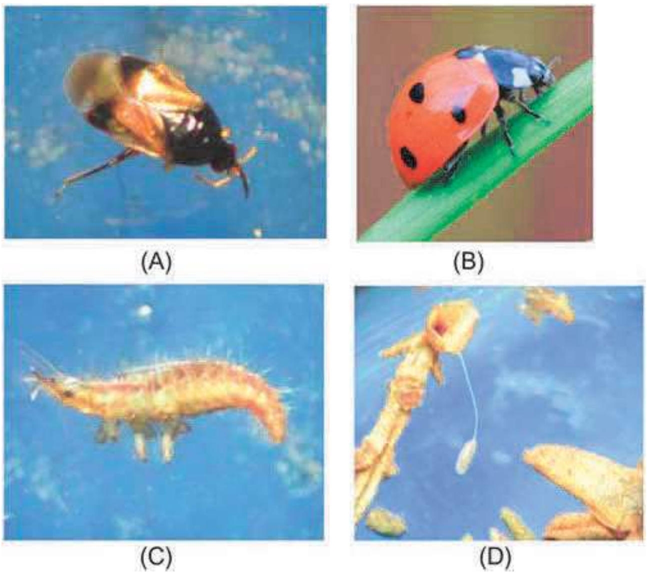

FIGURE 3.5 Some predators used for biological control: (A) true bugs (*Orius* sp.); (B) lady beetles (*Coccinela setempunctata*); (C) lacewing larvae; and (D) egg (*Chrysopa* sp.).

- *Lacewings* (Order Neuroptera)—adult lacewings can be predaceous, some feed on pollen or do not feed; larvae prefer to feed on aphids and other small insects and mites (Pappas et al., 2011; Loru et al., 2014);
- *Predatory flies* (Order Diptera)—mostly hover flies (family Syrphidae), aphid flies (family Chamaemyiidae), and predaceous midges (Cecidomyiidae); while adults feed on pollen, nectar, or do not feed, the larvae are predatory (Noma et al., 2005; Driesche et al., 2009; Joshi and Ballal, 2013; Satar et al., 2015).

Belonging to the invertebrate predators that provide a *naturally occurring biological control*, are praying mantids (Order Mantodea), ground beetles (Order Coleoptera, family Carabidae), ants (Order Hymenoptera, family Formicidae), and spiders (Order Araneae) (Beard and O'Neill, 2005).

Vertebrate predators (especially birds, e.g., ring-necked pheasant, *Phasianus colchicus*) are better known to the general public than most invertebrate predators (Stoate, 2002). However, the use of vertebrates for biological control is too unpredictable.

Parasitoids parasitize on other insects, usually as larvae (but some parasitoids may also kill many pests by direct host feeding on the pest eggs or larvae) and, unlike a true parasite, the parasitoid ultimately sterilizes, kills, or sometimes consumes the host (Longe, 2016).

Parasitoids are usually smaller than the hosts upon which they develop and typically only attack one stage of host (egg/larva/nymph/pupa/adult) (Memmott et al., 2000). However, parasitoids that complete their larval development on or in the body of other living insects, and require just a single host to complete development are often similar in size to their insect hosts (Cohen et al., 2005). Different species of parasitoids attack different life stages of the pest. Thus, *Trichogramma* spp., which attack the egg stage of insects, are known as egg parasitoids (Fatouros et al., 2008). Braconidae, such as *Cotesia glomerata*, which attack larvae are larval parasitoids and so on for adult or nymphal parasitoids (Wäckers, 2004). Parasitoid larvae kill their hosts near the end of the parasitoid's larval development. Adult parasitoids are free-living and usually feed on pollen, nectar, honeydew, or even the body fluids of their host (e.g., Wäckers, 2004). Parasitoids exhibit a number of different life habits and are themselves parisitized by secondary hyperparasites (Dent, 2000) (Table 3.2).

Parasitized immature stages of pests are usually differently colored. For example, stages of immature whiteflies parasitized with parasitic wasp, *Encarsia formosa* (Encyrtidae), are darker or black when late in the parasite development compared to yellowish to creamy healthy ones. Aphids are hosts for species in the subfamily *Aphidiinae* (Braconidae) such as *Aphidius* spp. and parasitized aphids, called "aphid mummies," appear puffed up, brown, and hardened (Tóth, 2012).

A *parasite* is a *pathogen* causing a disease on another organism (Table 3.3). Pathogens include bacteria, viruses, fungi, and

TABLE 3.2 Examples of Parasitoids

Beneficial Insect		Pest/crop Binomial
Order	**Species**	
Hymenoptera	*Aphidius colemani*	Aphids/vegetables
	Lysiphlebus testaceipes	
	Dacnusa sibirica	Leaf miners/vegetables
	Diglyphus iasea	
	Encarsia formosa	White flies/several
	Eretmocerus mundus	
	Amitus fuscipenis	
	Leptomastix dactylopii	Scale/citrus
	Hyposoter didimator	Caterpillars/several
	Cotesia kasak	
	Telenomus laeviceps	
	Trichogramma evanescens	

entomopathogenic nematodes. Pathogens and their metabolic products help to reduce pest populations and represent one of three principal categories of natural enemies used in applied biological control (Dent, 2000).

Most insect pathogens are relatively specific to certain groups of insects and certain life stages (Longe, 2016). Unlike chemical insecticides, these pathogens can take longer (several days) to kill or debilitate the target pest. Although they kill, reduce reproduction, slow growth, or shorten the life of pests, their effectiveness may depend on environmental conditions or host abundance. The degree of control by naturally occurring pathogens may be unpredictable.

Bacteria infect insects via their digestive tracts, so insects with sucking mouth parts, like aphids and scale insects, are difficult to control with bacterial biological control. A small number of entomopathogenic bacteria have been commercially developed for control of insect pests. These include *Lysinibacillus (Bacillus) sphaericus, Paenibacillus spp.*, *Serratia entomophila*, and several *Bacillus thuringiensis* subspecies (Winstanley and Rovesti, 1993). *Bacillus thuringiensis* (Bt) is a parasitic bacterium that occurs naturally in the soil and is the most widely applied species of bacteria used for biological control, with at least four subspecies used to control Lepidopteran (moth, butterfly), Coleopteran (beetle), and Dipteran (true flies) insect pests (Longe, 2016). It can be applied on leaves and other plant parts to control larvae

TABLE 3.3 Examples of Parasites

Beneficial Insect			Pest/crop Binomial	Ecological Relation
Group		Species		
Microorganisms	Bacteria	*Bacillus thurigiensis*	Caterpillars/several	Toxin
		Bacillus subtilis	Leaf miners/several	
		Streptomyces avermitilis	Leaf miners and acari/several	
	Fungi	*Beauveria bassiana*	*Ostrinia nubilalis*	Parasite
		Metharhizum anisopliae	Coleoptera, Lepidoptera	
		Verticilium lecanii	White flies	
	Nematode	*Steinernema feltiae*	Soil insects	
		Heterorhabditis bacteriophora	*Papillia japonica*	

(Bravo et al., 2007). *B. thuringiensis* subspecies *kurstaki* is the most widely used for control of pest insects of crops and forests, and *B. thuringiensis* subspecies *israelensis* and *Lysinibacillus (Bacillus) sphaericus* are the primary pathogens used for control of important pests that are vectors of human diseases. *B. thuringiensis* toxins are highly selective and with very limited environmental impact.

Viruses can be highly effective natural regulators against pests and diseases. There are six main groups of insect viruses but only three are sufficiently different from human viruses to be considered safe and these are: the nuclear polyhedrosis virus (NPV), the granulosis virus (GV), and the cytoplasmic polyhedrosis virus (CPV). These viruses produce an occlusion body, a structure that protects virus particles or virions. The occlusion body is resistant to environmental insults and could be considered analogous to a bacterial spore. Different strains of naturally occurring NPV and GV are present at low levels in many insect populations. Epizootics (Epizootic—contagious disease that attacks an unusual number of animals at the same time and in the same area and spreads quickly) can occasionally devastate populations of some pests, especially when insect numbers are high (Doelle et al., 2009; Tóth, 2012).

Some insect species are susceptible to infection by naturally occurring *entomopathogenic fungi*. Fungi are ubiquitous natural entomopathogens that have a considerable epizootic potential and can spread quickly through an insect population and cause its collapse. Although a large number of fungi species have been traditionally regarded as pathogens of arthropods, recent studies have demonstrated that they are plant endophytes, plant disease antagonists, rhizosphere colonizers, and plant growth promoters. These attributes provide possibilities to use fungi in multiple roles. In addition to arthropod pest control, some fungal species could simultaneously suppress plant pathogens and plant parasitic nematodes as well as promote plant growth (Winstanley and Rovesti, 1993; Lacey et al., 2015).

Entomopathogenic fungi do not need to be consumed by insects, because they penetrate the insect body through the cuticle and can infect in this way also sucking insects such as aphids and whiteflies that are not susceptible to bacteria and viruses. Fungus proliferates in the host's blood and invades the host's organs shortly before the host dies or it may kills the insect more quickly, possibly through the use of toxins that they produce. It generally takes several days for a fungus-infested host to die (Dent, 2000).

Presently, there are only a few commercialized microbial pesticides based on entomopathogenic fungi, but the genera *Beauveria*, *Metarhizium*, *Verticilium*, *Nomuraea*, and *Hirsutella* are of most interest for biological control. These fungi are often very specific to insects, including at least 14 species that attack aphids, and several others that act in a wide variety of insect pests, such as *Beauveria bassiana* that is used to control whiteflies, thrips, aphids, and weevils (Longe, 2016).

Nematodes that parasitize insects, known as *entomopathogenic nematodes*, have been described from 23 nematode families (Koppenhöfer and Fuzy, 2008). Of all the nematodes studied for biological control of insects, the families Steinernematidae and Heterorhabditidae have received the most attention because they possess many of the attributes of effective biological control agents (Grewal et al., 2008; Koppenhöfer and Fuzy, 2008; Lacey et al., 2015). They can kill their hosts in a relatively short period of time and have been used as classical, conservational, and augmentative biological control agents.

The infective stage of nematodes (third-stage larvae) can detect its host by responding to chemical and physical cues. When a host has been located, the nematodes penetrate into the insect body cavity, usually via natural body openings (mouth, anus, spiracles) or areas of thin cuticle. The third-stage infective larvae carry symbiotic bacteria in their guts and, after invading a host, release the bacteria (*Xenorhabdus* for steinernematids, *Photorhabdus* for heterorhabditids) (Burnell and Stock, 2000). The bacteria are responsible for killing the hosts very rapidly (2–3 days). The nematodes feed upon the bacteria, liquefy the host and mature into adults. Nematode generations continue to develop within the same cadaver and infective larvae exit when the density of nematodes is high and nutrients concentration is low.

The most important species are *Steinernema carpocapsae* against Lepidoptera and Coleoptera (Curculionidae and Chrysomelidae), *S. feltiae* against Diptera, *Heterorhabditis bacteriophora* against Lepidoptera and Coleoptera, and *Phasmarhabditis hermaphrodita* against slugs and snails (Koppenhöfer and Fuzy, 2008; Lacey and Georgis, 2012). The knowledge about target pests showning to be susceptible has increased in recent years, both in soil and aboveground habitats (Lacey et al., 2015)

Biological Control Strategies

There are three strategies for biological control: conservation, classical biological control, and augmentation. Historically, most emphasis has been placed on classical biological control, although more recently a great deal of effort has been directed to augmentative control (Tóth, 2012).

Conservation biological control involves environmental manipulation to enhance the survival, fecundity, longevity, and behavior of natural enemies in order to increase their effectiveness (Landis et al., 2000). Conservation biological control is an important part of crop pest management in organic farming. Conservation of natural enemies involves either reducing factors which interfere with the natural enemies or provides needed resources that help natural enemies. Examples of techniques that are used to improve food, habitat, reproduction sites, to beneficial insects, are the establishment of ecological infrastructures (infrastructures with ecological values within a radius of 150 m from the farm) (Franco et al., 2006) or the use of cover crops (Fig. 3.6).

Conservation relies on naturally occurring enemies that are well adapted to the target area and with relatively little effort the activity of these natural

FIGURE 3.6 (A) Ecological infrastructures and (B) cover crops at the Portuguese Douro region.

enemies can be observed. For example, lacewings, lady beetles, hover fly larvae, and parasitized aphid mummies are almost always present in aphid colonies. Fungus-infected adult flies are common after periods of high humidity.

The use of pesticides has a side effect on natural enemies. When a pesticide is used to control a pest, the natural enemies disappear too, either by dying or by migrating to another ecosystem (Thacker, 2002). Certain cultural practices can also damage the natural enemies or their habitats, e.g., removal of uncultivated areas, field margins, weedy areas, roadsides, etc.; soil cultivation; crop establishment; fertilization; use of growth regulators, or harvesting, especially at the critical periods of beneficial organisms' life cycles. These practices should be avoided.

Classical biological control, described as "*The intentional introduction of an exotic, usually co-evolved, biological control agent for permanent establishment and long-term pest control*" (Eilenberg et al., 2001), is often used against introduced pests which arrive in a new area and become permanently established without an associated natural enemy complex (Amaro, 2003).

New pests are constantly arriving accidentally or intentionally and leave their natural enemies behind. If they become a pest, introducing some of their natural enemies can be an important way of reducing the amount of harm they can do. The search for suitable natural enemies (parasitoids, predators, pathogens) should in principle include all organisms closely related to the target pest, with special consideration to those organisms, which affect pest density and distribution. For best results, a biological control agent requires a colonizing ability which will allow it to keep pace with the spatial and temporal disruption of the habitat caused by the pest (Driesche et al., 2009; Longe, 2016).

The first example of classical biological control dates back to the end of the nineteenth century, when Californian citrus orchards had suffered attacks from the Australian scale, *Icerya purchase*. This scale was successfully controlled with the introduction of its natural enemy, the coccinellid cardinal ladybird, *Rodolia cardinalis* (DeBach, 1964). Another successful example of this technique was the control of the woolly apple aphid, *Eriosoma lanigerum*, in Europe, through the introduction of its specific parasitoid *Aphelinus mali* and that of the San José scale, *Quadraspidiotus perniciosus*, through the introduction of the parasitoid *Prospaltella perniciosi* (van Lenteren and Manzaroli, 1999). A recent example is *Trichogramma ostriniae*, a small wasp that was introduced from China to control the European corn borer (*Ostrinia nubilalis*), one of the most destructive insects in North America (Longe, 2016).

At least 2700 arthropod biological control agents have been introduced worldwide for biological control (Cock et al., 2009). Classical biological control is estimated to be applied on 3.5 million km^2 (350 million hectares), which is about 8% of land under culture, and has very high benefit−cost ratios (about 20−500:1) (van Lenteren, 2012).

Augmentation is a method of increasing the population of a natural enemy by mass producing a pest in a laboratory and releasing it into the field at the correct time.

Mass rearings should be released at times when the pest is most susceptible and natural enemies are not yet present, or they can be released in such large numbers that few individuals go untouched by their enemies. The augmentation method relies upon continual human management and does not provide a permanent solution, unlike the classical or conservation approaches. There are two basic approaches to augmentation: inoculation (relatively few natural enemies are released at a critical time of the season) and inundation (millions of natural enemies are released) (Luck and Forster, 2003; Longe, 2016).

Augmentative biological control is applied worldwide, and more than 230 species of natural enemies are now commercially available for augmentative biological control (van Lenteren and Bueno, 2003; van Lenteren, 2012).

3.3.2.4 Biotechnical Control

Biotechnical control is the use of an insect physiological mechanism or environmental behavior, that will negatively affect the organisms' survival (Amaro, 2003).

Intentionally or not, insects communicate between themselves (intraspecific communication) and with members of other species (interspecific communication), to reproduce (to look for a mate, courtship), locate resources (food, nidification places), defend territory, camouflage or mimic other organisms, identify members of the same species, or even to warn other organisms of their own presence or to signal potential hazards (Reinhard, 2004; Cocroft and Rodríguez, 2005; Drosopoulos and Claridge, 2005).

Insects have many different ways of communicating (the process of transferring information between two [or more] individuals). They use their five senses to acquire information about their environment: hearing, sight, smell, taste, and touch.

Communication by smell and taste occurs based on the production and emission of semiochemicals (a pheromone or other chemical that conveys a signal from one organism to another so as to modify the behavior of the recipient organism). The emitter scatters the semiochemicals into the environment which are detected by other organisms. The insects have more or less specialized receptors located on their antennae, legs, etc. that allow them to detect the semiochemicals (insects can savor and smell these substances with almost all parts of their body!) (Reinhard, 2004).

Over the last 60 years, more than 3000 semiochemicals have been identified (Pojar-Fenesan and Balea, 2016). Semiochemicals, defined as behavior-modifying chemicals, are volatile organic compounds that transmit chemical messages; these can be pheromones—compounds used by insects for intraspecific communication—or allelochemicals—compounds used between individuals of different species for interspecific communication.

Pheromones can be divided into sex attractants (to help individuals of the opposite sex find each other), aggregation pheromones (to increase the concentration of insects at the pheromone source), alarm substances (to stimulate insects' escape or defense behaviors), trail-marking compounds (to mark a trail, for example, the way to a food source), and host marking pheromones (to mark the boundaries of a territory) (Reinhard, 2004).

Pheromones are widely used to disrupt pest ecology and reduce crop losses due to pests. They can be used for (1) mating disruption—high ambient pheromone concentrations to confuse males or to hide the trails of calling females (Gordon et al., 2005; Welter et al., 2005; Stelinski et al., 2009; Vassiliou, 2009), and (2) mass trapping—aggregate insects (both sexes) and attract them to specific devices (Chermiti and Abbes, 2012; Landolt et al., 2012; Chen et al., 2014; Hampton et al., 2014).

Mate disruption involves the use of sex pheromones to prevent male insects finding females and mating. The process is based on disturbing mating by saturating the atmosphere with synthetic pheromones released by dispensers that act as false sources. In an atmosphere saturated with the sexual pheromone, the males become disoriented and cannot locate the females, which emit pheromones at a lower concentration than the dispenser (Welter et al., 2005). The aim is to prevent mating, so that no eggs are formed, decreasing the population density. Thus, no damage is incurred in the area covered by the pheromone. By reducing the likelihood of successful mating through mating disruption, the infestation level decreases.

The release of sufficiently large quantities of synthetic sex pheromone (using dispensers) into the crop atmosphere interferes with mate location in four ways: adaptation or habituation (high concentrations of the pheromone make males unresponsive to or inhibit their ability to respond); camouflage or masking (the background level of the pheromone is high and uniform enough to mask the odor trail from a calling female), false trails (the males still sense and respond to the pheromone, but due to the numerous sources of pheromone in the field, the males spend time and energy following trails to false sources) or trapping (the pheromone dispenser is placed in a trap, the males respond to the pheromone and become trapped).

A variety of dispensing technologies are available to growers: microencapsulated pheromones (small droplets of pheromone enclosed within a polymer capsule), hand-applied dispensers (an impermeable reservoir fitted with a permeable membrane for regulating pheromone release, and a central pheromone-containing core sandwiched between two polymer films), hollow fibers (a short, impermeable plastic tube that is sealed at one end and filled with pheromone), and high-emission dispensers (a puffer with a pressurized aerosol filled with a pheromone, that puffs at fixed time intervals) (Welter et al., 2005).

Pheromones used in mating disruption are species-specific and are thus highly selective, and also pheromone active ingredients are naturally occurring compounds, nontoxic to humans and other nontarget organisms and do not leave residues on fruit and leaves because they are not applied directly to them.

Monitoring is critical to the successful implementation and maintenance of mating disruption and in keeping secondary pests under control.

Mating disruption has been successfully implemented against Codling moth (*Cydia pomonella*) (Fischbach, 2009; Stelinski et al., 2009) and the grapevine moth, *Lobesia botrana* (Gordon et al., 2005; Carlos et al., 2013). Pheromone emitters are placed throughout orchards or vineyards, just prior to bloom or when the first adults emerge, saturating the orchard with pheromone and males cannot find the females, so no eggs are laid. Several years of consecutive application of the method helps to reduce the damage caused by the pest, and avoids the use of pesticides.

Mass trapping is based on the concept of using species-specific synthetic chemical lures, such as sex and aggregation pheromones and food/host attractants, to attract insects to a trap where they are confined and die. Mass trapping using odor-baited traps is one of the older approaches to direct control of insects for population suppression and eradication (El-Sayed et al., 2006). The density and efficiency of traps as well as the strength of lures need to be sufficient to catch enough insects to reduce damage.

One of the most recent pests in Europe is the vinegar fly *Drosophila suzukii*, the spotted wing drosophila, a highly polyphagous invasive pest endemic to South East Asia (Landolt et al., 2012; Hampton et al., 2014). Its serrated ovipositor allows this fly to lay eggs on and damage unwounded ripening fruits, causing huge damage. Among the environmentally safe strategies that are available, mass trapping has been revealed to be very effective in several studies.

This technique is very easy to set-up, all the materials are reusable, they can be filled with the different lures and used to capture other insects, and they enable the use of insecticides to be avoided, reducing the risks of delaying harvesting or pesticide residues.

The disruption of an insect physiological mechanism can also be adopted in *area-wide management*: a coordinated and preventive approach that targets the entire pest populations in an entire region. It can be integrated with the sterile insect technique (male sterilization to reduce mating). This technique is often used against Diptera and Lepidoptera.

3.3.2.5 Physical and Cultural Control

Organic farming relies on methods which combine scientific knowledge of ecology and modern technology with traditional farming practices based on naturally occurring biological processes. The physical and cultural control methods, that aim at eliminating or reducing the amount of the pest or pathogen present in the field or to enhance the beneficials' activity, include crop rotation, intercropping, cover crops, mulches, and soil solarization to reduce pest and disease incidence. Other methods, such as flooding, deep plowing, fire and flaming, may also be used (Katan, 2010).

Crop rotation is an ancient and important agricultural practice with an important role in improving the quality of crops, soil fertility, and also, crop protection. Continuously cropping the same crop builds up the population levels of pests and pathogens that live, at least a part of their life cycle, in the soil (Yuliar et al., 2015). By defining a sequence of different crops on the same field—crop rotation—it is possible to reduce pest and pathogen populations just because they are not suited to the host plant. For example, crop rotations using Chinese chive (*Allium tuberosum*) and tomato have reduced the incidence of bacterial wilt (approximately 60%) because the root exudates of Chinese chive may prevent *R. solanacearum* from infecting tomato plants (Yu, 1999). Rotations are good for controlling host-specific pests and diseases such as potato cyst nematode and eyespot of cereals. They are not as effective against general pests such as slugs, and are unlikely to have any effect on migratory pests such as birds.

Another great benefit of rotations is the renewal of fertility and improving soil structure that is directly related to the ability of a crop plant to resist or tolerate insect pests and diseases and with soil biodiversity (Altieri et al., 2012; Tiemann et al., 2015; Venter et al., 2016). Data collected from several studies prove that longer rotations produced stronger positive effects on belowground communities. Positive ecological interactions between soils and pests should be enhanced to optimize agroecosystem function (Altieri et al., 2012).

Intercropping or *consociated species* refers to the special cropping system obtained by growing two or more species in the same space and time, whose association may generate reciprocal benefits. Agricultural specialists suggest intercropping has also the ability to reduce pests and diseases (Fig. 3.7A) (Shennan, 2007; Carrubba et al., 2008).

Intercropping contributes to crop protection by breaking pest and disease cycles, creating barriers to the spread of pests and diseases, enhancing arthropod biodiversity, namely natural enemies, by providing alternative food, shelter, and reproduction sites, and generating conditions for better plant health which are known to increase plant resistance. The use of consociated crops might also benefit from plant indirect defense mechanisms based on allelochemical effects: volatiles (alkaloids, monoterpenoids) produced by

FIGURE 3.7 (A) Intercropping, (B) cover crops, and (C) mulching.

plants that can influence, directly or indirectly, other organisms (plants, pests, diseases) (Fürstenberg-Hägg et al., 2013). The allelochemicals produced by plants are released by washing the leaves by rainfall or irrigation, through the root exudates, and by volatilization. Some examples of plants that help to avoid pests and diseases are, for example, *Artemisia absinthium* L, commonly called absinthium or wormwood, that repulses mammals, acari, cabbage butterfly, several flies and fungus like *Fusarium solani* or *Fusarium oxysporum*, or *Allium cepa* to control mites, ants, and storehouse pests (Chiasson et al., 2001; Moore et al., 2006; Stoleru and Sellitto, 2016).

Cover crops are crops planted to manage soil erosion, soil fertility, soil quality, water, weeds, pests, diseases, biodiversity, and wildlife in an agroecosystem (Fig. 3.7B) (Lu et al., 2000). As previously referred, they also provide habitat for beneficial predator insects, supplemental food source to insects and wild bees in the form of nectar from their flowers and act as non-host crops for nematodes and other pests in crop rotations (Nunes et al., 2015).

Another cultural practice that helps controlling pests and diseases is *mulching* (Fig. 3.7C): the use of a layer film of organic materials applied to the soil surface, blocking nearly all light from reaching the surface, to preserve moisture, improve the fertility and health of the soil, and reduce weed growth and infestation with different pests (Stoleru and Sellitto, 2016). In organic farming, mulches may be biodegradable (e.g., bark chips, straw, organic newspaper, killed cover crop residue left on the surface, biodegradable plastics or nets). It may be applied to bare soil or around existing plants. All mulch types suppress insects in comparison with bare soil.

Soil solarization is a nonpollutant method effective to control a variety of soil pests and diseases (Katan and DeVay, 1991). The method employs solar energy through a thin transparent film (0.03–0.05 mm) that is laid on the previously watered ground surface, during the warmest months of the year and for a period of time not less than 30 days. The soil should be prepared in order to ensure the homogeneity and perfect fragmentation of the soil, to a shallow depth, to obtain a plain and straight surface, inner condition to the application of the film in the ground (Fig. 3.8). The soil should be copiously

FIGURE 3.8 Soil solarization process: (A) soil preparation to obtain a plain and straight surface; (B) irrigation using gravity technique or other; (C) placing and stretching the transparent film; and (D) solarization for a period of 30 days during the warmest months of the year.

watered (with a volume of at least 30 mm of water per square meter), using irrigation by gravity or another technique, for for a period of two days. The presence of water in the soil is essential to increase the thermal conductivity, ensuring heat penetration into the soil and solarization efficiency.

The high temperature levels in solarized soil reach lethal and sublethal levels to pathogens, insects, and vertebrates (Yaduraju and Mishra, 2004; Vitale et al., 2010). It may be applied in vegetable crops, in presowing or preplantation, in greenhouses or outdoors. In perennial crops it should be used during preplantation or after the plantation stage, but in this case, its utilization should not be generalized. It should be done with adequate mobilization of the ground, achieving 20 or 30 cm depth.

Solarization success depends on the amount, depth, and duration of increased soil temperature, but also on the thermal sensitivity of the target organism and the density of the agent populations in the soil (Vitale et al., 2010; Yuliar et al., 2015). Soil solarization has proved to be effective in the control of plant diseases caused by soil fungi (*Fusarium oxyporum, Plasmodiophara brassicae, Pythium ultimum, Sclerotinia* spp., *Pyrenochaeta terrestris, P. lycopersici, Rhyzoctonia solani*, and *Verticillium dahlia*), nematodes (*Heterodera carotae* and *Meloidogyne* spp.), bacteria (*Agrobacterium tumefaciens*), and arthropods that live in the soil.

Other cultural practices, such as sowing and harvest timing, cultivation, and canopy management using green interventions, might contribute to reduce pest and disease severity (Costa et al., 2016; Stoleru and Sellitto, 2016).

Careful timing of sowing and harvesting operations may avoid pests, and to some extent diseases: early sowing spring oats and winter rye allows the plants to grow enough to avoid damage by fly larvae (*Oscinella frit*) or late carrot sowing ensures that plants emerge between the first and second flight periods of the carrot fly (*Psila rosae*) (Fidler and Webley, 1960; Berry et al., 1997; Huusela-Veistola et al., 2008).

Cultivations (or tillage) may also limit pest and disease attack. A well-prepared seed bed will allow the crop to grow quickly and avoid some problems, reducing the activity of invertebrates, such as slugs and leatherjackets, which require protection from the soil. Also, good trash burial will remove sources and disrupt soil organisms' life cycles (Stoleru and Sellitto, 2016).

Some invertebrate pests can be physically excluded from crops. For this, a barrier, such as fleece or fine plastic net, is required. This can be effective, for example, in excluding carrot fly from a crop of carrots, but it is only justified on valuable crops such as vegetables (Nunes et al., 2015).

3.3.2.6 *Biopesticides*

Based on the type of active ingredients, biopesticides may be microbial pesticides or biochemical pesticides. *Microbial pesticides* are products used to control plant diseases made from beneficial *microorganisms* (e.g., a bacterium, fungus, virus, or protozoan) as the active ingredient or the metabolites they produce (Bonaterra et al., 2011). *Biochemical pesticides* are naturally occurring substances that control pests by nontoxic mechanisms. Conventional pesticides, by contrast, are generally synthetic materials that directly kill or inactivate the pest. Biochemical pesticides include substances, such as insect sex pheromones, which interfere with mating, as well as various scented plant extracts that attract insect pests to traps.

Microbial Pesticides

Microbial pesticides consist of a microorganism such as a *bacterium*, *fungus*, *virus*, or *protozoan,* as the active ingredient formulated to be applied as conventional pesticides. Microbial pesticides can control different kinds of pests, although each active ingredient is relatively specific for its target pest(s) (Bravo et al., 2007). For example, there are bacteria that control certain insects, fungi, or nematodes (Table 3.4). This characteristic reduces the concern with pest or disease resistance and the negative impact on the environment and public health (Ragsdale and Sisler, 1994; Montesinos and Bonaterra, 2009).

TABLE 3.4 Bacterial Pesticides, Target Pests, and Action Mode (Costa et al., 2016)

Bacteria species	Category	Target pest(s)	Action Mode
Bacillus thuringiensis (Bt)	Insecticide	Lepidoptera	Digestive System
Bacillus subtilis (Bs)	Bactericide	Bacterial and fungal pathogens such as *Rhizoctonia, Fusarium, Aspergillus*	Colonizes plant root and competes
Bacillus sphaericus	Insecticide	Mosquito larvae	Produce two groups of proteinaceous toxins
Pseudomonas fluorescens	Fungicide \Bactericide	Several fungal, viral, and bacterial diseases, such as frost-forming bacteria	Crowds out and controls the growth of plant pathogens
Pasteuria spp.	Nematicide	Endoparasitic nematodes and microscopic worms that feed on plant roots	The spores of the bacteria germinate in the nematode, reproducing and causing death
Streptomyces lydicus	Fungicide	Root rot and damping-off pathogens, such as *Fusarium, Rhizoctonia, Pythium, Phytophthora, Phymatotrichum omnivorum, Aphanomyces, Monosporascus, Armillaria, Sclerotinia, Verticillium, Geotrichum*, powdery and downy mildews, *Botrytis, Monilinia, Anthracnose, Mycosphaerella citri, Sclerotinia, Alternaria*, and *Erwinia*	Colonizes plant roots, competing with root pathogens for physical space and nutrients. Foliar applications result in colonization of aboveground plant parts It may act as a parasite of fungal plant pathogens

Bacterial biopesticides have been used to control plant diseases, nematodes, insects, and weeds. The most successful insect pathogen used for insect control is the bacterium *Bacillus thuringiensis* (Bt), which presently is

~2% of the total insecticidal market (Bravo et al., 2011), a naturally occurring bacterium common in soils throughout the world. The target insect species are determined by whether the particular *Bt* produces a protein that can bind to a larval gut receptor, thereby causing the insect larvae to starve. Different strain of Btproduce a different mix of proteins which can specifically kill one or a few related species of insect larvae. Bt is almost exclusively active against larval stages of different insect orders and kills the insect by disruption of the midgut tissue, followed by septicemia (Raymond et al., 2010). Bt action relies on insecticidal toxins that are active during the pathogenic process but these bacteria also produce an array of virulence factors that contribute to insect killing (Bravo et al., 2005).

There are several insecticides based on various subspecies, such as *B. thuringiensis israelensis* (Bti), with activity against mosquito larvae, black fly, fungus gnats, and related dipterans species; *B. thuringiensis kurstaki* (Btk) and *B. thuringiensis aizawai* (Bta) against lepidopteran larval species; *B. thuringiensis tenebrionis* (Btt), against coleopteran adults and larvae; and *B. thuringiensis japonensis* (Btj) strain *buibui*, against soil-inhabiting beetles (Khater, 2012).

Fungal biopesticides can be used to control insects, mites, plant diseases including other fungi or bacteria, nematodes, and weeds. Like bacteria, they may act by out-competing the targeted pathogen or producing toxins (Table 3.5). *Trichoderma harzianum* is a fungi that acts as a fungicide, targeting *Pythium, Rhizoctonia*, and *Fusarium*.

Nematodes are colorless, nonsegmented, and elongated roundworms. Many are parasitic to plants and cause serious damage to crops and other types of plants. However, some are beneficial, attacking insect pests, and can be used to control a wide range of insect pests including a variety of caterpillars, cutworms, crown borers, grubs, corn root worm, cranefly, thrips, fungus gnats, and beetles (Miles et al., 2000; Kaya and Lacey, 2007; Grewal et al., 2008; Koppenhöfer and Fuzy, 2008) (Table 3.6). As we have seen above, the two main nematodes effectively used as biological insecticides are the families Steinernematidae and Heterorhabditidae.

Baculoviruses are one of the largest and most diverse group of entomopathogenic viruses, a large group of naturally occurring double-stranded DNA viruses (Table 3.7). They are mandatory disease-causing organisms that can only reproduce within a host insect. Among the 15 or more families of invertebrates viruses, only those having virus particles (virions) occluded within a proteinaceous matrix, an occlusion body, are of interest for crop protection (families Entomopoxviridae or entomopoxviruses, Reoviridae or cypoviruses, and Baculoviridae or baculoviruses) (Kaya and Lacey, 2007), but only baculoviruses are used as pesticides (Szewczyk et al., 2006).

Individual baculoviruses usually have a narrow host range limited to a few closely related species, mostly of the order Lepidoptera, Hymenoptera, and Coleoptera. Baculoviruses infect arthropods and they do not replicate in

TABLE 3.5 **Fungal Pesticides, Target Pest(s), and Action Mode (Costa et al., 2016)**

Fungi Species	Category	Target Pest(s)	Action Mode
Beauveria bassiana	Insecticide	Foliar-feeding insects	White muscadine disease
Trichoderma viride/ harzianum	Fungicide	Soil- and seedborne fungal diseases, such as root rot, caused by organisms like *Fusarium* etc.	Mycoparasitic
Trichoderma and *Paecilomyces*	Fungicide/ Nematocide	Soil fungal pathogens and nematodes	Digests the cell walls of pathogens
Muscodor albus	Biofumigant	Bacteria and soilborne and seedborne diseases and pests	Releases volatile toxins
Verticillium lecani	Insecticide	Sucking pests like, aphids, jassids, mealybugs, white flies, mites, etc.	Entry of fungal hyphae into insect body, parasitization and sporulation and killing of insects in about 5–7 days
Beauveria bassiana Pseudomonas fluoresens	Insecticide	Borers, thrips, etc.	Digesting of insect cuticle enzymatically by fungus and parasitization, and control of insects in about 5–7 days
Paecilomyces lilacinus	Nematicide	All types of nematodes	Entry of fungal hyphae into insect body, parasitization and sporulation and killing of insects in about 5–7 days

vertebrates, plants, or microorganisms. The granulosis virus of *Cydia pomonella*, the codling moth, and the nuclear polyhedrosis virus of *Heliothis/Helicoverpa* spp., the corn earworm, are two popular examples.

Protozoa are single-celled eukaryotic organisms that live in water and soil. Most protozoa feed on bacteria and decaying organic matter, but several are insect parasites that are able to reduce the offspring produced by infected insects. Although protozoan pathogens play a significant role in the natural

TABLE 3.6 Entomopathogenic Nematodes, Target Pest(s), and Action Mode (Costa et al., 2016)

Nematode Species	Category	Target Pest(s)	Action Mode
Steinernema glaseri	Insecticide	White grubs (scarabs, especially Japanese beetle, *Popillia sp.*)	Penetrates insect pests and releases cells of their symbiotic bacteria from their intestines into the hemocoel
S. kraussei		Black vine weevil, *Otiorhynchus sulcatus*	
S. carpocapsae		Turfgrass pests, billbugs, cutworms, armyworms, sod webworms, chinch bugs, codling moth, cranberry girdler, dogwood borer and other clearwing borer species, black vine weevil, peach tree borer	
S. feltiae		Fungus gnats (*Bradysia spp.*), shore flies, western flower thrips	
S. scapterisci		Mole crickets (*Scapteriscus spp.*)	
S. riobrave		Citrus root weevils (*Diaprepes spp.*)	
Heterorhabditis bacteriophora		White grubs (scarabs), cutworms, black vine weevil, flea beetles, corn root worm	
H. megidis		Weevils	
H. indica		Fungus gnats, root mealybug, grubs	
H. marelatus		White grubs (scarabs), cutworms, black vine weevil	

limitation of insect populations, only a few appear to be suited for development as bioinsecticides although there use has not been very successful until now (Koul, 2011). The genus *Nosema* and *Vairimorpha* attack lepidopteran and orthopteran insects and apparently prefer hoppers to other insects.

TABLE 3.7 **Baculoviruses, Target Pest(s), and Action Mode (Costa et al., 2016)**

Baculovirus	Category	Target Pest(s)	Action Mode
Nucleopolyhedrosis virus (NPV)	Insecticide	Specific for Lepidoptera (88%), Hymenoptera (6%), and Diptera (5%)	Infects digestive cells in larvae gut
Granulosis virus (GV)		Specific species of Lepidoptera	

An example of a natural biocontrol agent of grasshoppers, locust, and crickets is *Nosema locustae*, a commercially available microbial pesticide that is nontoxic to humans and other mammals. The microorganism control agent infects and weakens young grasshoppers and affects female ability to reproduce.

Some yeast species that naturally occur in plants have been developed into products that help to control postharvest decay and/or stimulate the plant's immune system (Khater, 2012). For example, a biopesticide for the control of post-harvest gray mold (*Botrytis cinerea*) and blue mold (*Penicillium expansum*) is *Candida olephila* Strain O. It is used on fruits, vegetables, and other plants, acting through competition for nutrients and precolonization of plant wound sites.

Spinosad results from the aerobic fermentation of the actinomycete (soil filamentous bacteria) species *Saccharopolysora spinose*. It is a fast-acting and effective biopesticide that affects the insects' nervous system, affecting body control. Spinosad is used with positive results in several pest insect species including beetles, caterpillars, thrips, aphids, whiteflies, and leafhoppers and grasshoppers (Pinóia, 2012). Spinosad has a relatively low level of toxicity in mammals and is approved for organic use.

Biochemical Pesticides

Biochemical pesticides are naturally occurring substances that control pests by nontoxic mechanisms, including semiochemicals (insect sex pheromones and kairomones), scented plant extracts that attract insect pests to traps, naturally occurring repellents, natural plant and insect regulators, and secondary metabolites like alkaloids, terpenoids, and phenolics from various plants (Costa et al., 2016)

Botanical biopesticides, chemicals extracted or derived from plants, are often slow-acting crop protectants usually safe to humans and the environment. Several botanical pesticides may be used in organic farming (Table 3.8).

TABLE 3.8 Botanical Biopesticides, Target Pest(s), and Action Mode (Costa et al., 2016)

Botanical Biopesticides	Category	Target Pest(s)	Action Mode	Toxicity
Pyrethrum	Insecticide	Pickleworms, aphids, leafhoppers, spider mites, harlequin bugs, cabbage worms	Disrupts sodium and potassium ion exchange and interrupts the transmission of nerve impulses	High toxicity to bees, fishes
Neem	Insecticide	Cutworms, armyworms, sodworms	Acts on digestive, nervous and hormonal systems	–
Rotenone	Insecticide	Spittlebugs, aphids, potato beetles, harlequin bugs, chinch bugs, spider mites, carpenter ants	Inhibits cellular respiration	High toxicity to fishes, suspicion of relation with Parkinson's disease
Ryania	Insecticide	Codling moths, Japanese beetles, squash bugs, potato aphids, thrips, corn earworms, silkworms	Prevents muscles from contracting, causes paralysis	Low mammalian toxicity
Sabadilla	Insecticide	Grasshoppers, codling moths, moths, armyworms, aphids, cabbage loopers, blister beetles, squash bugs, harlequin bugs	Affects nerve cell membrane action, causes loss of nerve function, paralysis	High toxicity to honey bees
Garlic oil	Insecticide	Cabbage moths, cabbage loopers, earwigs,	Repellent or toxic and antifeedant on insects	–

(Continued)

TABLE 3.8 (Continued)

Botanical Biopesticides	Category	Target Pest(s)	Action Mode	Toxicity
		leafhoppers, whiteflies, aphids		
Essential oils	Insecticide/ fungicide bactericide/ herbicide	All types of insects, bacteria, fungi, and nematodes	Destroy cell membrane	–

Pyrethrum is the powdered, dried flower head of the pyrethrum daisy *Chrysanthemum cinearifolium*. Pyrethrins refers to the six related insecticidal compounds that occur naturally in the crude flower dust, that possess toxic effects by disrupting the sodium and potassium ion exchange process in insect nerve fibers and interrupting the normal transmission of nerve impulses (Khater, 2012). Pyrethrin insecticides are extremely fast-acting and cause an immediate paralysis of insects. Pyrethrum products represent 80% of the total market of global botanical insecticides (Isman et al., 2010) and are used by organic growers because of their low mammalian toxicity and environmental nonpersistence (Khater, 2012). Nevertheless, as they are **highly toxic to fish and bees** and moderately toxic to birds, they **should be avoided in organic farming**.

Derived from the neem tree (*Azadirachta indica*), *neem* contains several chemicals, including "azadirachtin," which affects the reproductive and digestive process of insects. Extracts from neem are effective against more than 500 species of insects and arthropods with great interest as a source of natural drugs and environmentally friendly pesticides (Isman et al., 2010; Mehlhorn, 2011). Neem pesticide products are made by crushing neem tree seeds, and then using water or a solvent, such as alcohol, to extract the pesticidal constituents. In addition to being an insecticide, it has been used as a fungicide, nematicide, and bactericide, including insect growth-regulating qualities (Ware and Whitacre, 2004).

Neem seeds are a rich storehouse of over 100 terpenoids and diverse nonisoprenoids (Khater, 2012). The main ingredient of neem is azadirachtin, a tetranortriterpenoid. It exhibits antifeedant, insect repellent, and insect sterilization properties. The azadirachtin mimics an insect hormone, acting on its hormonal system, and inhibits their digestion, metamorphosis, and reproduction. In general, chewing insects are more affected than sucking insects and insects that undergo complete metamorphosis are also generally more affected than others (Dubey, 2010). Neem is nontoxic to birds and mammals, noncarcinogenic, and does not lead to development of resistance.

Rotenone is an insecticidal flavonoid extracted from the roots of *Lonchocarpus* species with a broad-spectrum contact and ingestion activity, particularly effective against leaf-feeding beetles and certain caterpillar pests. Rotenone is a powerful inhibitor of cellular respiration, acting primarily on nerve and muscle cells, and causing rapid cessation of feeding. Rotenone is **extremely toxic to fish**, paralyzing them, and there is at present a growing concern about its relation to Parkinson's disease (Betarbet et al., 2000).

Ryania is obtained from the roots and stems of *Ryania speciosa*. The extracted alkaloid is effective as a contact or stomach poison and directly prevents muscles from contracting, causing paralysis (binding the calcium channels in the reticulum causing calcium ions flow to the cell) and death (Singh, 2014). Although it does not produce rapid knockdown paralysis, it does cause insects to stop feeding soon after ingesting it. It can be used on a wide range of insects and mites, including potato beetle, lace bugs, aphids, and squash bug. Its residual activity is lower than other botanicals.

Sabadilla is a compound derived from the ripe seeds of *Schoenocaulon officinale*. The aged and heated seed, or when treated with alkali, forms or activates several insecticidal alkaloids. The alkaloids in sabadilla are known collectively as veratrine alkaloids, and of these alkaloids, cevadine and veratridine are the most active. Sabadilla affects the nerve cell membrane action, causing loss of nerve function, paralysis, and death (Singh, 2014). Sabadilla is mainly a broad-spectrum contact or ingestion poison effective against certain true bugs, caterpillars, leafhoppers, and thrips. The active alkaloids degrade rapidly in air and sunlight, and have little residual toxicity, but sabadilla is **highly toxic to honey bees**, and its use **must be avoided**.

Several studies have shown that *garlic* (*Allium sativum L.*) is effective against fungi such as *Phytophthora capsici* or insects, such as the maize weevil, *Sitophilus zeamais*, but it also possesses acaricidal, nematicidal, and bactericidal properties (Li and Zhihui, 2008; Nwachukwu and Asawalam, 2014).

Several other *essential oils* from various plant species, such as oregano, cinnamon, thyme, wintergreen clove, peppermint, and rosemary, composed of complex mixtures of volatile monoterpenes and sesquiterpenes, have activity against pest insects and plant pathogenic fungi ranging from antifeedant, repellent, oviposition deterrent, growth regulatory, and antivector activities (Tripathi et al., 2009). Monoterpenes are toxic to animal tissue, causing a reduction of intact mitochondria and golgi bodies, disturbing respiration and photosynthesis, and reducing cell membrane permeability. They also serve as chemical messengers for insects and other animals. Essential oils have shown positive results against *Periplaneta americana, Drosophila melanogaster*, and *Helicoverpa armigera*.

Other Pesticides Used in Organic Farming

Soaps are frequently used in organic farming, to control aphids and other soft-bodied insects by breaking down the waxy cuticle of the insect. Soaps or fatty acid salts are man-made fatty acids. Since plants also have waxy cuticles, soaps may also damage some plants (in fact, some soaps may be used as organically approved herbicides). These products rely on a bicarbonate salt (usually potassium bicarbonate) as the active ingredient, which disrupts the potassium or sodium ion balance within the fungal cell, causing the cell walls to collapse. Potassium alum with a concentration of 0.4% shows good efficacy against lice, caterpillars, and shell-less snails and potassium soap in combination with horsetail extract is successfully used against mites (red spider), larvae of the Colorado beetle, and the cabbage aphid (Stoleru and Sellitto, 2016).

Minerals are used widely for disease control (Costa et al., 2016). Some minerals (e.g., *copper*, *sulfur*) are toxic to various organisms, including aquatic species, and they should be used with caution. Sulfur can be used as a dust, powder, or liquid, to control fungal diseases including powdery mildew, rust, leaf blight, and fruit rot, and arthropods such as spider mites, psyllids, and thrips. Copper is used to control fungi and bacterial diseases. Copper-based materials are considered synthetic, and are allowed with restrictions. Copper ions link to chemical groups present in proteins of germinating spores and disrupt their function by the denaturation of cellular proteins. Copper must be applied on the plant surface before the spore germinates and reapplied as plants grow to maintain coverage and prevent disease establishment. Kaolin is a common mineral clay that results from weathering of aluminous minerals and acts as a physical barrier, preventing insects from reaching vulnerable plant tissue, or as a repellent by creating an unsuitable surface for feeding or egg-laying.

3.4 FINAL CONSIDERATIONS

The principles of arthropod, pathogen and weed management in organic systems involve the adoption of ecologically sound practices designed to prevent damaging levels and minimizing the need for curative solutions. This crop protection strategy, called IPM, is based on the knowledge of biological interactions, and information on the crop and the surrounding environment. Concern about balancing the ecosystem (soil quality, plant nutrition, biodiversity) contributes to obtaining plants that are more able to resist infection and feeding insects, reducing the severity of pests and diseases.

In organic farming, famers should first use preventive mechanisms—indirect crop protection methods—and if necessary suppressive measures—direct, or curative, crop protection methods. Crop diversification and rotation and the implementation of ecological infrastructures are indirect measures that might contribute to reducing pest and disease incidences in farms. Direct pest and disease control includes pheromones, habitat management, biological control, mechanical or physical control. Some natural pesticides (biopesticides) are approved in organic farming systems, but should only be used if no other solution exists and avoided as much as possible.

Decision-making in organic pest management is based on the assessment of the intervention necessity, through risk assessment, economic thresholds or predictive models, and considering the balance of risk factors.

Risk assessment (pest identification and monitoring) is essential to decide whether the pest can be tolerated or if control is needed. In this case, the information collected will also help to select the most effective management methods and the best time to use them. The direct measures should only be used if the pest or disease density has reached a level at which management action should be taken to prevent an increasing pest population from reaching the economic injury level.

Nonchemical control methods—regulatory, genetic, cultural, physical, biological, and biotechnical—are the core options in organic farming, and only when none of the previous methods are enough to control a pest or disease, should biopesticides be used.

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