Chapter 2
Principles of IPM in Cultivated Crops and Implementation of Innovative Strategies for Sustainable Plant Protection

Jürgen Gross and Gerhard Gündermann

Abstract In this chapter, the concepts of integrated pest management (IPM) and integrated production (IP) are explained, and the most important definitions are given. The legal framework for regulation of IPM in the European Union is specified, and the general principles are explained. The EU Framework Directive requires that all EU member states develop a national action plan (NAP), which ensures that a set of eight general principles of IPM are implemented by all professional pesticide users. Along these principles, the authors present an overview on important examples for new and innovative developments and attempts in plant protection to enhance sustainable agriculture. They give short introductions in selective and biorational pesticides, anti-resistance strategies, and new methods for monitoring pest insects by semiochemicals. Furthermore, they give an overview on the diversity of nonchemical methods in pest control. These methods include mating disruption techniques mediated by semiochemicals and substrate vibrations, mass trapping, attract-and-kill techniques, the use of repellents, antifeedants and deterrents, as well as more complex push-and-pull strategies.

2.1 Introduction

The concept of integrated pest management (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. Pests in cultivated crops include pest animals (including arthropods, mollusks, nematodes,

---

J. Gross (✉)
Federal Institute for Cultivated Plants, Institute for Plant Protection in Fruit Crops and Viticulture, Julius Kühn-Institut, Schwabenheimer Str. 101, 69221 Dossenheim, Germany
e-mail: Juergen.Gross@julius-kuehn.de

G. Gündermann
Federal Institute for Cultivated Plants, Julius Kühn-Institut, Messeweg 11/12, 38104 Braunschweig, Germany
e-mail: Gerhard.Guendermann@julius-kuehn.de

A.R. Horowitz, I. Ishaaya (eds.), *Advances in Insect Control and Resistance Management*, DOI 10.1007/978-3-319-31800-4_2

and vertebrates), plant pathogens (viruses, bacteria including phytoplasmas and *Liberibacter*, fungi), and weeds. IPM aims to suppress pest populations below a specific economic injury level (EIL). The EIL is defined as “The lowest population density of a pest that will cause economic damage; or the amount of pest injury which will justify the cost of control” (Stern et al. 1959). Regarding IPM, currently 67 different definitions are available in the worldwide literature. The Food and Agriculture Organization of the United Nations (FAO), e.g., defines IPM as follows: “Integrated Pest Management means the careful consideration of all available pest control techniques and subsequent integration of appropriate measures that discourage the development of pest populations and keep pesticides and other interventions to levels that are economically justified and reduce or minimize risks to human health and the environment. IPM emphasizes the growth of a healthy crop with the least possible disruption to agro-ecosystems and encourages natural pest control mechanisms” (FAO 2015). The International Organization for Biological and Integrated Control-West Palearctic Regional Section (IOBC-WPRS) defines further the concept of integrated production (IP). It is a concept of sustainable agriculture developed in 1976 which has gained international recognition and application. The concept is based on the use of natural resources and regulating mechanisms to replace potentially polluting inputs. The agronomic preventive measures and biological/ physical/chemical methods are carefully selected and balanced taking into account the protection of the environment and the health of farmers and consumers (Boller et al. 2004). The 2004 IOBC Standard for Integrated Production covers ecological, ethical, and social aspects of agricultural production as well as aspects of food quality and safety. The current set of IP guidelines and related tools has proven helpful and inspirational for farmers’ organizations looking for a feasible way to work with integrated production in the premium food segment (Boller et al. 2004).

2.2 Regulation of IPM in Europe

IPM in Europe is regulated in Directive 2009/128/EC. A definition similar to the definition published by the FAO is provided by the European Union Framework Directive on the sustainable use of pesticides in Art. 3 No. 6: “Integrated pest management” means careful consideration of all available plant protection methods and subsequent integration of appropriate measures that discourage the development of populations of harmful organisms and keep the use of plant protection products and other forms of intervention to levels that are economically and ecologically justified and reduce or minimize risks to human health and the environment. “Integrated pest management” emphasizes the growth of a healthy crop with the least possible disruption to agroecosystems and encourages natural pest control mechanisms” (Directive 2009/128/EC). The general principles are published in Annex III of Directive 2009/128/EC. Establishing incentives for professionals to implement guidelines for IPM can be found in Art. 14 No. 5 and the obligation of

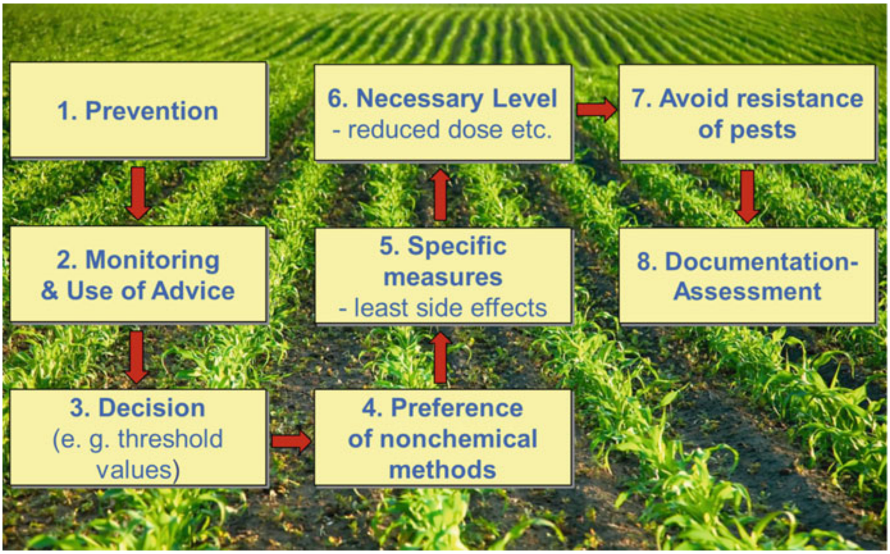

Fig. 2.1 The set of eight general principles of IPM

EU-ME to report how to ensure the general principles of IPM in Art. 14 No. 4: Member states shall describe in their national action plans (NAP) how they ensure that the general principles of integrated pest management as set out in Annex III are implemented by all professional users by 1 January 2014. Thus, all 27 member states of the European Union are to transpose this directive into national legislation.

The EU Framework Directive requires that all EU member states develop an NAP, which ensures that a set of eight general principles (Fig. 2.1) of IPM (Annex III) are implemented by all professional pesticide users compulsory from 1 January 2014 (European Union 2009):

1. Prevention and suppression of harmful organisms
2. Monitoring, warning, forecasting, and the use of advice
3. Decision-making (e.g., threshold values)
4. Preference of nonchemical methods
5. Pesticide selection (least side effects)
6. Necessary level (reduced pesticide use)
7. Anti-resistance strategy
8. Documentation and assessment

Member states shall establish appropriate incentives to encourage professional users to implement crop- or sector-specific guidelines for integrated pest management on a voluntary basis. Public authorities and/or organizations representing particular professional users may draw up such guidelines. Member states shall refer to those guidelines that they consider relevant and appropriate in their NAPs (Directive 2009/128/EC, Art 14 No. 5).

In Germany, guidelines (cultural or sector-related production) are developed through associations of farmers, gardeners, and associations with scientific support under a strong consideration of practical relevance. The Integrated Production Commission of the IOBC-WPRS, e.g., elaborates crop-specific guidelines for integrated production of agricultural crops that have formed the basis for IPM programs in Switzerland, the Czech Republic, and Italy. Further, it develops and standardizes methods of testing effects of pesticides on beneficial organisms. In the fulfillment of its objectives, it collaborates with other international organizations, notably FAO, WHO, the Commission of the European Union (CEU), and the European Plant Protection Organization (EPPO). The IOBC-WPRS has already published crop-specific IP guidelines for a large number of crops (pome fruits, stone fruits, arable crops, grapes, soft fruits (berries), olives, citrus, and field grown vegetables). Further guidelines have to be developed for sugar beet (Gummert et al. 2012), wine growing, urban greening, etc. Up to 2018, guidelines should be available in every plant production system including minor crops (mostly vegetables, fruits, nursery stock, and ornamentals). At present, around 30 % of farmers observe guidelines 3 years after their establishment.

The guidelines must include the following topics:

1. Prevention: crop rotation, cultivation (non-plow tillage), resistance, etc.
2. Observation: the use of learned lessons
3. Decision: check of pest development and thresholds
4. Preference of nonchemical methods: biotechnical, physical, and technical methods, biologicals, etc.
5. Pesticide: specific, environmental, reduced dose, and necessary level
6. Documentation and control of results

For minor crops, sustainability can only be realized by the continued availability of crop protection solutions for pest control. Since the last decade, European farmers have far less new technology to drive agricultural production than their competitors in other regions of the world. In Europe, particularly the number of minor crops without viable solutions for plant protection has increased (Lamichhane et al. 2015). This is mainly because many effective compounds once registered on an EU level have not been reauthorized due to stricter regulation processes. The limited range of available pesticides has increased the risk of pesticide resistance development since, in the absence of several pesticides with various modes of action, farmers must apply only a narrow spectrum of active ingredients (Lamichhane et al. 2015). Research and development (R&D) for new crop protection products needed by European farmers is in decline, according to an analysis of market trends in the EU and around the world. A recent study reveals that the number of active ingredients being developed and introduced in the EU is steadily decreasing – even as global expenditure on agricultural R&D is on the rise (Anonymous 2013). The share of global crop protection R&D focused on European markets has decreased from 33 % in the 1980s to only 16 % today. Moreover, the European market's share of total worldwide R&D expenditure for new product development in agricultural life sciences is just 7.7 %

today compared to 33 % in the 1980s (Anonymous 2013). The most important reasons behind the reduction in R&D investment in crop protection products for the European market are the nonacceptance of GMOs and the harsh regulatory environment. Thus, the future development and implementation of innovative IPM solutions are very important.

2.3 Demonstration Farms for IPM in Germany

In the year 2007, the network of reference farms, called "Demonstration Farms for Integrated Plant Protection" (DF-IPP), an important component of the NAP in Germany, has been started. It is a joint project of the Federal Ministry of Food and Agriculture of Germany (BMEL), the plant protection services in the federal states and the Julius Kühn-Institut, Federal Research Centre for Cultivated Plants (JKI). The network focuses on surveying representative farms to demonstrate the feasibility of IPM in representative regions and crops and to obtain annual data on plant protection product (PPP) uses in major crops and to generate additional information relevant to crop protection. All PPP treatments are evaluated to determine their actual use intensities based on the so-called treatment frequency index (TFI) and the necessary minimum of PPP use, as determined by experts from the plant protection services (Hommel et al. 2014). Various checklists were developed to evaluate the implementation of IPM on demonstration farms (Peters et al. 2015). The following parameters are used to explain differences in TFI scores between farms, within or between regions: field and farm size, soil quality, previous crop, tillage, sowing date, cultivar resistance, and the use of decision support systems (Hommel et al. 2014). The data are pooled for four selected regions (north, east, south, and west) and for Germany in total. In arable farming, e.g., about 75 farms are surveyed annually. Integrated plant protection (IPP) guidelines are to be applied in the model and demonstration project DF-IPP (Hommel et al. 2014). Thus, new developments and innovative strategies for sustainable plant protection can easily be implemented in practice and according to a circle of measurements and assessments (Fig. 2.1) under practical conditions evaluated (Gündermann 2014). The outcome of the IPM measures and assessments will be communicated to farmers and public (Fig. 2.2).

2.4 Certification of Plant Protection Knowledge

Professional users of PPPs must be certified (plant protection certification) to use plant protection products. Undergoing training in handling and using plant protection products, related to the certification, is voluntary in all member states. The state certificate includes a written and oral exam or an approved associated

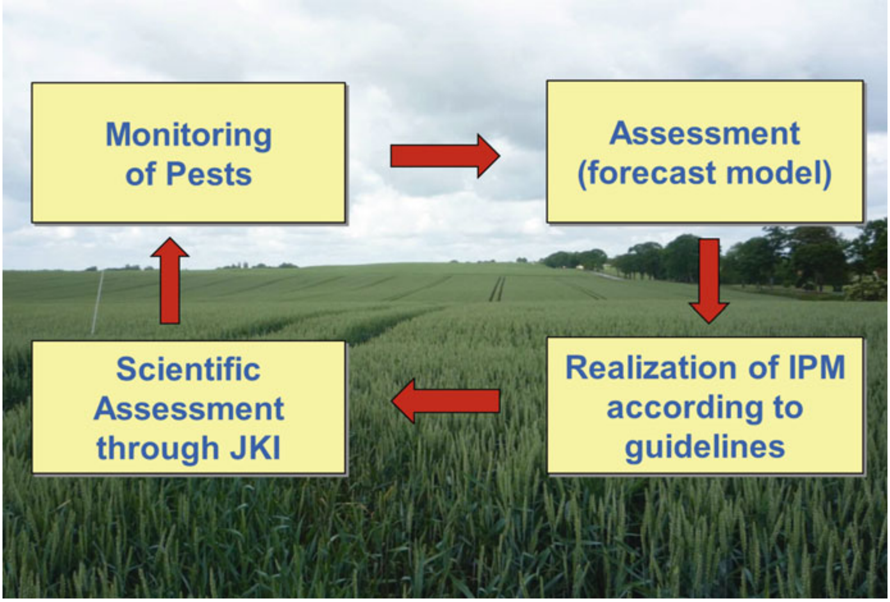

Fig. 2.2 The circle of measurements and assessments on DF-IPP in Germany (Gündermann 2014)

degree. Independent training and advice for farmers are regulated by the national plant protection acts and accompanied regulations, such as the regulation on professional knowledge. In Germany, e.g., each of the 16 federal states is responsible for advice, awareness raising, and training, in particular on good plant protection practice including IPP and the implementation of NAP measures (Hommel et al. 2014). The federal states are also required to diagnose and monitor pests, carry out field experiments and PPPs trials, and maintain databases and forecasting platforms in the Internet. The German Internet platform ISIP (Information System for Integrated Plant Production: www.isip.de) integrates weather data in disease models and provides regional decision support in major crops (Racca et al. 2011). In Denmark, an extensive monitoring system is operating linked to the farm advisory system, which has a high impact on reduced pesticide uses (Kudsk and Jensen 2014). In Germany, the organization of public extension differs from state to state (Hommel et al. 2014). Very common schemes to distribute knowledge are training courses in winter time and open field days during the growing season. During the latter, information is mainly transmitted via online portals, monitoring systems, prognosis models, and specific decision support systems (DSS) (Hommel et al. 2014). Professional users, advisors in plant protection, and distributors of PPPs have to renew their certification every 3 years. In Germany, training details and education topics have to be specified by region and crop through the responsible authorities (Freier and Zornbach 2008).

2.5 Development of Innovative Plant Protection Strategies

The future of agricultural plant production is threatened by the emergence of pest resistance and a declining availability of active substances in plant protection products (Lamichhane et al. 2015). Additionally, invasive species like the brown marmorated stink bug (*Halyomorpha halys*) (Leskey et al. 2012) and the spotted wing drosophila (*Drosophila suzukii*) are expanding their native range to other continents (Cini et al. 2014; Vogt et al. 2012). Thus, the numbers of severe agricultural pests registered in pest information databases like the "Pest Information Wiki" (PestinfoWiki Contributors 2015) are increasing continuously. In conclusion, there is a need to design cropping systems less dependent on synthetic pesticides, which integrate innovative plant protection strategies (Barzman et al. 2014). According to the eight principles of IPM formulated in Annex III of Directive 2009/128/EC, we give in the following an overview on important examples for new developments and attempts in plant protection.

2.5.1 Selective and Biorational Pesticides

Pesticides applied on crops shall be as specific as possible for the target pest and shall have the least side effects on human health, nontarget organisms, and the environment (Principle 5 of IPM – pesticide selection). Thus, those insecticides that are efficacious against target pests but less detrimental to beneficials, the so-called biorational pesticides, should be the first choice in IPM programs. This term describes any type of insecticide including botanicals and microbials active against pest populations but relatively innocuous to nontarget organisms and therefore nondisruptive to biological control (Schuster and Stansly 2015). Applied separately, biorational pesticides may perform with less biocidal power and appear more costly than conventional synthetic pesticides. By integrating several alternative methods, they may generate synergies resulting in satisfactory pest control (Barzman et al. 2015). In Chaps. 5 and 8 of this book, examples will be presented dealing with this aspect (Wise 2016; Akhatar and Isman 2016).

2.5.2 Anti-resistance Strategies

Where the risk of resistance against a plant protection measure is known and where the level of harmful organisms requires repeated application of pesticides to the crops, available anti-resistance strategies should be applied to maintain the effectiveness of the products. This should include the use of or rotation of multiple pesticides with different modes of action (Barzman et al. 2015) (Priciple 7 of

IPM – anti-resistance strategies). Some studies on this important principle are given in Chaps. 11, 12, 13, 14, 15, and 16 of this book.

2.5.3 *Monitoring of Pest Insects by Semiochemicals*

Harmful organisms must be monitored by adequate methods and tools. Such adequate tools should include trappings and observations in the field as well as scientifically sound warning, forecasting, and early diagnosis systems, where feasible, as well as the use of advice from professionally qualified advisors (Barzman et al. 2015) (Principle 2 of IPM – monitoring). IPM strategies require a full understanding of the biology and life history of a pest organism and its natural enemies within any ecosystem (Dent 1991). While the adult life stage will be the target for monitoring of pest insects by semiochemicals regularly, in some cases, other ontogenetic stages could be the target of monitoring depending of their biology and ecology. For monitoring of, e.g., mosquito populations, so-called ovitraps mimicking their preferred breeding sites were developed acting as an early warning signal by counting the eggs to preempt any impending dengue outbreaks (Jacob and Bevier 1969). Also in moth control, the monitoring of caterpillars or eggs could be easier than very mobile adult stages (see below). For innovative monitoring methods, which use semiochemicals for luring different life stages of target insects, only adult and egg monitoring are appropriate because no methods exist for luring relative immobile larval stages by chemical components in traps, while the mating and egg laying behavior of adult insects could be much better exploited for the development of chemically lured monitoring traps.

2.5.3.1 Adult Monitoring

Traps consisting of sticky foils or filled with toxic fluids are often equipped with artificial dispensers emitting synthetic sexual pheromones. They are widely used for monitoring the population dynamics of insect pests, which is the basis for decisions regarding chemical control and for calculating the optimal timing for spraying insecticides. Many insect pheromones have been identified in the past and are commercially available today for trapping moths, beetles, flies, and many other pest insects. The Internet database “Pherobase” lists hundreds of sexual pheromones for monitoring purposes (El Sayed 2014), and many of them are today commercially available. Traps equipped with these species-specific lures have allowed for significant advancement of IPM decision-making. However, they also have some weaknesses: the amount of caught specimen is not only influenced by population densities but also by weather conditions, dispenser specifications, and the actual reach of attractive plumes from traps (Miller et al. 2015). Finally, they have to compete against the natural sources of pheromones, mainly female insects themselves, as male-produced pheromones are very rare (Gross 2013). Key parameters influencing the number of trapped organisms from any specified distance of origin from the trap are the probabilities that the trap is found (findability) and that the organism is captured after arriving at the trap (efficiency) and retained (retention) until the trap is emptied by the farmer (Miller et al. 2015).

Besides pheromones, also allelochemicals can be used as lures in traps. Recently, new findings have been reported for psyllids, which could be used for the development of new chemically lured traps for monitoring and also mass trapping (Mayer et al. 2008a, b, 2009, 2011; Rid et al. 2016). In this case, also compounds with a high specificity for the target pest should be used to reduce bycatches of beneficial insects (Weintraub and Gross 2013). The emission rates of the attractive compounds, often plant-produced kairomones, have to be multiple times higher than by using pheromones.

2.5.3.2 Egg Monitoring

Even though in most cases eggs are more difficult to monitor in the field than adults, the advantage of monitoring the egg stage is established in systems, in which robust degree-day models exist for the period of time for egg development, before the damaging larval stage begins. The use of egg traps, e.g., equipped with kairomones from almond, is common and recommended in IPM for monitoring the navel orangeworm (*Amyelois transitella*) in the USA and Mexico (Anonymous 2002). This method is applied to determine when navel orangeworm eggs will hatch in relation to hull split of infested almonds so a chemical treatment can be timed precisely (Anonymous 2002). The European grapevine moth *Lobesia botrana* and European grape-berry moth *Eupoecilia ambiguella* (Lepidoptera: Tortricidae) are the most damaging insect pests in European viticulture. Larvae injure fructiferous organs by feeding and thus promote infestation with bacteria and fungi, such as gray mold *Botrytis cinerea*. To achieve effective chemical control, insecticide treatments have to be conducted before hatching of the larvae. For this purpose, an egg monitoring is necessary but not practicable. To prevent immoderate insecticide application, which would not be in compliance to IPM, a decision support system for growers is needed, which enables the timing and necessity of pest control. Such a tool, called “moth oviposition card” (M-OVICARD) consisting of volatile and nonvolatile compounds, supported by visual and tactile cues, is currently under development (Greif et al. 2015). The number of eggs, deposited on such a monitoring card, should correlate with actual pest infestation in grape vines and may help to determine the perfect spraying time, resulting in a reduced amount of applied insecticides (Greif et al. 2015).

2.5.4 Nonchemical Methods

Sustainable biological, biotechnical, physical, and other nonchemical methods must be preferred to chemical methods if they provide satisfactory pest control (Principle 4 of IPM – nonchemical methods) (Barzman et al. 2015). Plant protection strategies based on olfactory, gustatory, or acoustic signals are very divers and have a high potential to improve existing IPM strategies. For instance, there are many possibilities for the integration of semiochemical use in IPM strategies. Infochemicals convey information in interactions between individuals, leading in the receiver to a behavioral or physiological response. We distinguish between pheromones, which mediate interactions between organisms of the same species, and allelochemicals, which mediate interactions between two individuals that belong to different species (Dicke and Sabelis 1988). In most cases of pest control, pheromones are used due to their high species specificity. Sex pheromones are both used for monitoring of pest insects and for disturbing mating behavior (Gross 2013; Harari 2016, Chap. 6). Aggregation pheromones can be used for mass trapping, but this type of pheromone occurs only in a few known species (Gross 2013). For the so-called attract-and-kill or lure-and-kill systems, an attractive compound (a pheromone or a kairomone) is combined with a toxic component, like an insecticide or pathogenic microorganism. Ultimately, the potential of infochemicals for plant protection can be used in complex push-and-pull strategies.

2.5.4.1 Mating Disruption by Semiochemicals

The most prominent and environmentally friendly application method for pheromones in plant protection is the mating disruption technique. Females emit an airborne trail of sex pheromones, the so-called pheromone plume, which may be used by males to locate them. This technique exploits the male insects' natural response to follow the corresponding plume by introducing artificial dispensers emitting synthetic pheromones into their habitat. The synthetic pheromone is a volatile organic chemical designed to mimic the species-specific sex pheromone produced by the female insect. It is important to divide between competitive and noncompetitive mating disruption (Miller et al. 2015). Under competitive attraction operating in a crop treated with multiple point dispensers of synthetic pheromone, the frequency with which males find calling females is reduced because males are diverted from orienting to females or traps due to preoccupation with more numerous nearby dispensers that first attract responders and then arrest and possibly deactivate them (Miller et al. 2010). In contrast, noncompetitive disruption includes masking of females by pheromone dispensers and desensitization of responder sensory systems without first requiring attraction (Miller et al. 2010). Consequently, the male population experiences a reduced probability of successfully locating and mating with females, which can lead to termination of breeding followed by the collapse of insect infestation (Witzgall et al. 2010). The Internet database

"Pherobase" currently lists 149 species, for which mating disruption techniques have been proven, and 133 of these are Lepidoptera (El Sayed 2014). To date, important successes include codling moth *Cydia pomonella* in pome fruit, oriental fruit moth *Grapholita molesta* in peaches and nectarines, tomato pinworm *Keiferia lycopersicella* in vegetables, pink bollworm *Pectinophora gossypiella* in cotton (Welter et al. 2005), and omnivorous leafroller *Platynota stultana*, European grapevine moth *L. botrana*, and grape-berry moth *E. ambiguella* in vineyards (Gross 2013; Welter et al. 2005). The use of the mating disruption technique has been explored against stored-product pests such as *Plodia interpunctella* and *Sitotroga cerealella* (Fadamiro and Baker 2002). While most successes have been with Lepidoptera, research on stink bugs and beetles showed promising results (McBrien et al. 2002; Millar et al. 2002).

2.5.4.2 Mating Disruption by Substrate Vibrations

Mating disruption is generally based on sex pheromones and allows sustainable pest control resulting in strong reduction of pesticides sprayed (Witzgall et al. 2010). A very original and innovative approach in mating disruption using substrate vibrations was recently published by Eriksson et al. (2012). They applied disruptive acoustic signals (calls from a rival male) to grapevine plants through a supporting wire which decreased the mating frequency of the leafhopper *Scaphoideus titanus*, significantly. Read more on this new strategy in Chap. 9 of this book (Polajnar et al. 2016). In case that both acoustic and chemical signals are involved in courtship behavior like known from *Drosophila* (Fabre et al. 2012) or pear psyllids (Eben et al. 2014; Guedot et al. 2009; Lubanga et al. 2014), the acoustic mating disruption system could be supplemented by specific pheromone dispensers.

2.5.4.3 Mass Trapping

For the biological control of species that produce aggregation pheromones, mass trapping systems can be developed. Mass trapping is a direct control strategy, in which large numbers of pests are captured and removed from the system. Excellent results of the mass trapping technique were obtained in Central and South America by using sophisticated pheromone traps emitting male-produced aggregation pheromones of different weevil species, e.g., the West Indian sugarcane weevil, the banana weevil, and the American palm weevil (Giblin-Davis et al. 1996). In oil palm plantations in Central and South America, the palm weevil (*Rhynchophorus palmarum*) is a vector of the lethal red ring nematode. Today, the principal control method is a pheromone-based mass trapping, using one trap per acre (Oehlschlager et al. 2002). The key biological factors appear to be the relatively long life and slow reproductive rate of the tropical weevils and the fact that the aggregation pheromones attract both sexes. Success is critically dependent on efficient mass trapping to remove weevils faster than they can reproduce (Welter et al. 2005). Although there are only a few examples of this technique with a satisfactory effectiveness in temperate regions, two prominent examples are known from the control of the bark beetle *Ips typographus* in Europe and the Mountain pine beetle *Dendroctonus ponderosae* in North America (Witzgall et al. 2010). Allelochemicals like kairomones are less used in mass trapping as pheromones but are sometimes used in combination. A well-known example for an effective kairomone is the pear ester (ethyl (*E*,*Z*)-2,4-decadienoate), a characteristic volatile component of ripe pear. This kairomone is an attractant for adult and larval stages of codling moth *C. pomonella*. Its identification has allowed the development of several new approaches to successful monitoring and mass trapping of this pest (Light et al. 2001; Knight and Light 2001; Knight et al. 2002). In total, 111 compounds are listed in "Pherobase," which have the potential for mass trapping applications (El Sayed 2014), but only a few are used in today's pest control strategies.

2.5.4.4 Attract and Kill (Lure and Kill)

Another approach using sex pheromones or other attractive compounds is the attract-and-kill or lure-and-kill method. A viscous paste, gel, or a spray containing an attractant mixed with an insecticide, sterilant, or insect pathogen (e.g., entomopathogenic fungus or granulosis virus) can be distributed as small droplets, dollops, or a film on twigs or leaves of cultivated plants, eliminating individuals that contact the lure. When a female sex pheromone was used as attractant and a contact insecticide as toxin, males are lured to the droplet, try to mate with it and finally get killed (Charmillot et al. 2000). Huang et al. (2013) suggest that an effective attract-and-kill device should keep target insects from contacting the pheromone source directly to avoid desensitization of the olfactory apparatus, while providing a surface that allows them sufficient time to contact the toxicant and acquire a lethal dosage. Conventional attract-and-kill formulations in which sex pheromones are mixed with an insecticide would discourage moths contacting the insecticide surface for prolonged times. Thus, the better approach would be to spatially separate the sex pheromone or another desensitizing attractant from the toxicant (Huang et al. 2013). A newly developed prototype device for the control of the oriental fruit moth *G. molesta* was reported recently: It consisted of a fabric pouch that was impregnated with a contact insecticide and baited with a separate female sex pheromone lure, which was placed inside the pouch (Huang et al. 2015). This construction provided a large insecticide-treated surface for males to interact with but also prevented them from directly contacting the attractant for minimizing the risk of moths overloading their sensory system with sex pheromones (Huang et al. 2015). In other cases, an insect could be lured by a plant kairomone like pear ester and killed by an insecticide or granulosis virus after feeding on the droplet (Light 2007). Many limitations of mass trapping by aggregation pheromones also apply to attract-and-kill strategies that target males only. Depending on how the system is implemented, it may also interfere with the male's location of females through false-trail following, as well as the primary effect of the male's attraction to insecticide-laced baits (Welter et al. 2005). In total, 35 allelochemicals are listed in "Pherobase," which have the potential as new lures in attract-and-kill applications (El Sayed 2014). In conclusion, the attract-and-kill technique is a promising approach for IPM, but all knowledge on the biology and behavior of the target pest organisms must be included in the development of more efficient devices (Huang et al. 2013).

2.5.4.5 Repellents, Antifeedants, and Deterrents

There are actually rare examples for the use of repellent components in pest control. Some products containing repellent components, which produce a displeasing smell for mammals like deers, rodents, or wild boar, are commercially available. Throughout the sub-Saharan African countries, in which populations of the African elephant (*Loxodonta africana*) exist, farmers come into conflict with these pachyderms. Attracted by nutritious crops on the fields, they destroy substantial amounts of harvest by crossing through the plantations and feeding on the crops. As this species is protected and listed as a threatened species by the IUCN Red List and therefore must not be killed (Blanc 2008), new ways need to be found to repel or at least not attract the pachyderms to fields. It was shown recently that garlic, ginger, and lemon grass, plants which contain higher amounts of secondary plant products, were less attractive to elephants than maize (Gross et al. 2016). However, they may not be completely unpalatable or even repellent to them, but their activity could cause an avoidance behavior, which terms the active compound an antifeedant. The selection of appropriate, less attractive, or even unpalatable crops might be a solution for the agricultural sector in or close to elephant dwelled habitats to tackle these conflicts (Gross et al. 2016).

For the control of insect pests, both in greenhouse or field, no repellents have been approved so far worldwide. But there are some research activities trying to develop oviposition deterrents, e.g., for the invasive pest *D. suzukii* in the field (Stensmyr et al. 2012; Wallingford et al. 2015). The alcohols geosmin and 1-octen-3-ol were found to be deterrent to females of *D. suzukii* in laboratory choice tests (Wallingford et al. 2015). Furthermore, field experiments revealed that fewer eggs were observed in fruits at harvest and fewer adult *D. suzukii* were reared from fruits associated with 1-octen-3-ol odors than control fruit of cultivated red raspberry (Wallingford et al. 2015). In other cases, repellents are combined with attractants to so-called push-and-pull strategies (see below).

2.5.4.6 Push-and-Pull Strategies

More complex approaches for using the potential of allelochemicals in plant protection are the so-called push-and-pull strategies (Khan et al. 2010). They consist of cropping systems, in which specifically chosen companion plants are grown in between and around the main crop. Some of these companion plants (intercrop) release infochemicals that repel insect pests from the main crop ("push" component). Furthermore, crops which attract insect pests more strongly than the main crop are planted in its surroundings ("pull" component) (Cook et al. 2007). Future directions for improving existing push-and-pull strategies or the development of new techniques may also include biotechnical applications consisting of artificial dispensers emitting synthetic repellent compounds and traps supplied with synthetic attractants.

2.6 Conclusion

As the R&D for new chemical pesticides needed by European farmers is in decline, the resulting limited range of available pesticides has increased the risk of pesticide resistance development (Lamichhane et al. 2015). Thus, new attempts in the development of nonchemical methods for plant protection in IPM will help to enhance sustainable control of pest organisms and to reduce the amount of applied pesticides. The likeliness of successful pest control will be improved by a combination of different techniques using volatile chemicals for monitoring and semiochemicals as well as vibrational signals for direct control of pest organisms together with a controlled application of biorational or synthetic pesticides. Last but not least, by integrating also functional ecology aspects in IPM strategies like the impact of "ecosystem services" (Wise and Whalon 2009) delivered by native pollinators and pest organisms' natural enemies (pathogens, predators, parasitoids) will be the way leading to a sustainable agricultural crop production in the twenty-first century.

Acknowledgments The authors thank the editors A. Rami Horowitz and Isaac Ishaaya for the invitation to write this chapter and the anonymous reviewers for their constructive comments, which helped us to improve the manuscript. We thank Annett Gummert and Silke Dachbrodt-Saaydeh (Julius Kühn-Institut, Germany) for providing literature. We are grateful to Eva M. Gross (Schriesheim, Germany) for linguistic corrections of the manuscript.

References

Akhtar Y, Isman MB (2016) Development of semiochemicals and diatomaceous earth formulations for bed bug pest management. In: Horowitz AR, Ishaaya I (eds) Advances in insect control and resistance management. Springer, Cham

Anonymous (2002) Integrated pest management for almonds. University of California, statewide IPM project, Division of Agriculture and Natural Resources, Publication 3308

Anonymous (2013) R&D trends for chemical crop protection products and the position of the European Market. A consultancy study undertaken by Phillips McDougall Ltd., UK on behalf of European Crop Protection (ECPA), Brussels, Belgium

Barzman MS, Bertschinger L, Dachbrodt-Saaydeh S, Graf B, Jensen JE, Jorgensen LN, Kudsk P, Messéan A, Moonen AC, Ratnadass A, Sarah JL, Sattin M (2014) IPM policy, research and implementation: European initiatives. In: Peshin R, Pimentel D (eds) Integrated pest management, experiences with implementation, global overview, vol 4. Springer, London, pp 415–428

Barzman M, Bàrberi P, Birch AN, Boonekamp P, Dachbrodt-Saaydeh S, Graf B, Hommel B, Jensen J, Kiss J, Kudsk P, Lamichhane JR, Messéan A, Moonen A-C, Ratnadass A, Ricci P, Sarah J-S, Sattin M (2015) Eight principles of integrated pest management. Agron Sustain Dev 2015(35):1199–1215

Blanc J (2008) *Loxodonta africana*. In: IUCN 2013. IUCN Red list of threatened species. Version 2013.1. www.iucnredlist.org. Assessed on 28 Aug 2013

Boller EF, Avilla J, Jörg E, Malavolta C, Wijnands F, Esbjerg P (2004) Integrated production: principles and technical guidelines, 3rd edition. IOBC WPRS Bull 27(2):1–50. ISBN 92-9067-163-5

Charmillot P-J, Hofer D, Pasquier D (2000) Attract and kill: a new method for the control of the codling moth *Cydia pomonella*. Entomol Ex Appl 94:211–216

Cini A, Anfora G, Escudero-Colomar LA, Grassi A, Santosuosso U, Seljak G, Papini A (2014) Tracking the invasion of the alien fruit pest *Drosophila suzukii* in Europe. J Pest Sci 87:559–566. doi:10.1007/s10340-014-0617-z

Cook SM, Khan ZR, Pickett JA (2007) The use of ‘push–pull’ strategies in integrated pest management. Annu Rev Entomol 52:375–400

Dent DR (1991) Insect pest management. CAB International, Wallingford

Dicke M, Sabelis MW (1988) Infochemical terminology: should it be based on cost-benefit analysis rather than origin of compounds? Funct Ecol 2:131–139

Eben A, Mühlethaler RC, Gross J, Hoch H (2014) First evidence of acoustic communication in the pear psyllid *Cacopsylla pyri* L. (Hemiptera: Psyllidae). J Pest Sci 88(1):87–95

El-Sayed AM (2014) The Pherobase: database of pheromones and semiochemicals. http://www.pherobase.com. Assessed 30 Oct 2015

Eriksson A, Anfora G, Lucchi A, Lanzo F, Virant-Doberlet M, Mazzoni V (2012) Exploitation of insect vibrational signals reveals a new method of pest management. PLoS One 7(3):1–5

Fabre CCG, Hedwig B, Conduit G, Lawrence PA, Goodwin SF, Casal J (2012) Substrate-born vibratory communication during courtship in *Drosophila melanogaster*. Curr Biol 22:2180–2185

Fadamiro HY, Baker TC (2002) Pheromone puffs suppress mating by *Plodia interpunctella* and *Sitotroga cerealella* in an infested corn store. Entomol Ex Appl 102:239–251

Food and Agriculture Organisation of the United Nations (FAO) (2015) http://www.fao.org/agriculture/crops/core-themes/theme/pests/ipm/en/. Assessed on 25th Oct 2015

Freier B, Zornbach W (2008) Zur Qualifizierung und Weiterbildung der Berater und Trainer in den Pflanzenschutzdiensten Deutschlands. Nachrichtenbl Deut Pflanzenschutzd 60(9):205–208

Giblin-Davis RM, Pena JE, Oehlschlager AC, Perez AL (1996) Optimization of semiochemical-based trapping of *Metamasius hemipterus sericeus*. J Chem Ecol 22:1389–1410

Greif A, Rid M, Gross J, Hoffmann C (2015) Guiding tour: M-Ovicard – a decision support system for integrated pest management of grapevine moths. IOBC Working Group meeting “Integrated Protection and Production in Viticulture”, Vienna, Austria

Gross J (2013) Drugs for bugs: the potential of infochemicals mediating insect-plant-microbe interactions for plant protection and medicine. In: Gang DR (ed) Phytochemicals, plant growth, and the environment, vol 42, Recent advances in phytochemistry. Springer, New York, pp 79–93

Gross EM, McRobb R, Gross J (2016) Growing of alternative crops reduces crop losses due to elephants. J Pest Sci. 89:497–506. doi:10.1007/s10340-015-0699-2.

Guédot C, Millar JG, Horton DR, Landolt PJ (2009) Identification of a sex attractant pheromone for male winterform pear psylla, *Cacopsylla pyricola*. J Chem Ecol 35:1437–1447

Gummert A, Ladewig E, Märländer B (2012) Guidelines for integrated pest management in sugar beet cultivation—weed control. J Cultiv Plants 64(4):105–111

Gündermann G (2014) Principles of IPM in cultivated crops. Talk given at 10th European Congress of Entomology, University of York, 3–8 August

Harari A (2016) Disruption of insect reproductive systems as a tool in pest control. In: Horowitz AR, Ishaaya I (eds) Advances in insect control and resistance management. Springer, Cham

Hommel B, Dachbrodt-Saaydeh S, Freier B (2014) Experiences with implementation and adoption of integrated plant protection (IPP) in Germany. In: Peshin R, Pimentel D (eds) Integrated pest management. Springer, Dordrecht. doi:10.1007/978-94-007-7802-3_18

Huang J, Gut LJ, Miller JR (2013) Separating the attractant from the toxicant improves attract-and-kill of codling moth (Lepidoptera: Tortricidae). J Econ Entomol 106:2144–2150

Huang J, Gut LJ, Grieshop M (2015) Development of a new attract-and-kill technology for Oriental fruit moth control using insecticide impregnated fabric. Entomol Ex Appl 154:102–109. doi:10.1111/eea.12259

Jakob WL, Bevier GA (1969) Application of ovitraps in the US *Aedes aegypti* eradication program. Mosq News 29:55–62

Khan ZR, Midega CAO, Bruce TJA, Hooper AM, Picket JA (2010) Exploiting phytochemicals for developing a 'push–pull' crop protection strategy for cereal farmers in Africa. J Exp Bot 61(15):4185–4196

Knight AL, Light DM (2001) Attractants from 'Bartlett' pear for codling moth, *Cydia pomonella* (L.), larvae. Naturwissenschaften 88:339–342

Knight AL, Potting RPJ, Light DM (2002) Modeling the impact of a sex pheromone/kairomone attracticide for management of codling moth (*Cydia pomonella*). Act Horticult 584:215–220

Kudsk P, Jensen JE (2014) Experiences with implementation and adoption of integrated pest management in Denmark. In: Peshin R, Pimentel D (eds) Integrated pest management, experiences with implementation, global overview, vol 4. Springer, London, pp 467–486

Lamichhane JR, Arendseb W, Dachbrodt-Saaydeh S, Kudsk P, Roman JC, van Bijsterveldt-Gels JEM, Wick M, Messéana A (2015) Challenges and opportunities for integrated pest management in Europe: a telling example of minor uses. Crop Prot 74:42–47

Leskey TC, Hamilton GC, Nielsen AL, Polk DF, Rodriguez–Saona C, Bergh JC, Herbert DA, Kuhar TP, Pfeiffer D, Dively G et al (2012) Pest status of the brown marmorated stink bug, *Halyomorpha halys*, in the USA. Outlooks Pest Manag 23:218–226

Light DM (2007) Experimental use of the micro-encapsulated pear ester kairomone for control of codling moth, *Cydia pomonella* (L.), in walnuts. IOBC Bull 30(4):133–14

Light DM, Knight AL, Henrick CA, Rajapaska D, Lingren B, Dickens JC, Reynolds KM, Buttery RG, Merrill G, Roitman J, Campbell BC (2001) A pear-derived kairomone with pheromonal potency that attracts male and female codling moth, *Cydia pomonella* (L.). Naturwissenschaften 88:333–338

Lubanga UK, Guédot C, Percy DM, Steinbauer MJ (2014) Semiochemical and vibrational cues and signals mediating mate finding and courtship in Psylloidea (Hemiptera): a synthesis. Insects 5:577–595

Mayer CJ, Vilcinskas A, Gross J (2008a) Phytopathogen lures its insect vector by altering host plant odor. J Chem Ecol 34:1045–1049

Mayer CJ, Vilcinskas A, Gross J (2008b) Pathogen-induced release of plant allomone manipulates vector insect behavior. J Chem Ecol 34:1518–1522

Mayer CJ, Jarausch B, Jarausch W, Jelkmann W, Vilcinskas A, Gross J (2009) *Cacopsylla melanoneura* has no relevance as vector of apple proliferation in Germany. Phytopathology 99:729–738

Mayer CJ, Vilcinskas A, Gross J (2011) Chemically mediated multi-trophic interactions in a plant-insect vector-phytoplasma system compared with a partially nonvector species. Agricult Forest Entomol 13:25–35

McBrien HL, Millar JG, Rice RE, McElfresh JS, Cullen E, Zalom FG (2002) Sex attractant pheromone of the red-shouldered stink bug *Thyanta pallidovirens*: a pheromone blend with multiple redundant components. J Chem Ecol 28:1797–81

Millar JG, Daane KM, McElfresh JS, Moreira JA, Malakar-Kuenen R, Guillen M, Bentley WJ (2002) Development and optimization of methods for using sex pheromone for monitoring the mealybug *Planococcus ficus* (Homoptera: Pseudococcidae) in California vineyards. J Econ Entomol 95:706–714

Miller JR, McGhee PS, Siegert PY, Adams CG, Huang J et al (2010) General principles of attraction and competitive attraction as revealed by large cage studies of moths responding to sex pheromones. Proc Natl Acad Sci U S A 107:22–27

Miller JR, Adams CG, Weston PA, Schenker JH (2015) Trapping of small organisms moving randomly. Springer, Cham. doi:10.1007/978-3-319-12994-5

Oehlschlager AC, Chinchilla C, Castillo G, Gonzalez L (2002) Control of red ring disease by mass trapping of *Rhynchophorus palmarum* (Coleoptera: Curculionidae). Flor Entomol 85:507–513

PestinfoWiki Contributors (2015) 'Main Page', PestinfoWiki. Available at http://wiki.pestinfo.org/w/index.php?title=Main_Page&oldid=322337. Accessed 30 Oct 2015

Peters M, Freier B, Holst F, Goltermann S, Büttner C (2015) Checklist for evaluating the implementation of integrated plant protection on demonstration farms for integrated plant protection in arable crops used in Mecklenburg-Western Pomerania. Ges Pflan 67:33–44

Polajnar J, Eriksson A, Virant-Doberlet M, Mazzoni V (2016) Developing a bioacoustic method for mating disruption of a leafhopper pest in grapevine. In: Horowitz AR, Ishaaya I (eds) Advances in insect control and resistance management. Springer, Cham

Racca P, Kleinhenz B, Zeuner T, Keil B, Tschöpe B, Jung J (2011) Decision support systems in agriculture: administration of weather data, use of geographic information systems (GIS) and validation methods in crop protection warning service. In: Jao C (ed) Efficient decision support systems-practice and challenges from current to future. InTech, Rijeka, pp 331–354

Rid M, Mesca C, Ayasse M, Gross J (2016) Apple proliferation phytoplasma influences the pattern of plant volatiles emitted depending on pathogen virulence. Front Ecol Evol 3:152. doi:10.3389/fevo.2015.00152

Schuster, Stansly (2015) http://ipm.ifas.ufl.edu/pdfs/Biorational_Insecticides.pdf. Assessed 25 Oct 2015

Stensmyr MC, Dweck HKM, Farhan A, Ibba I, Strutz A, Mukunda L, Linz J, Grabe V, Steck K, Lavista-Llanos S, Wicher D, Sachse S, Knadsen M, Becher PG, Seki Y, Hansson BS (2012) A conserved dedicated olfactory circuit for detecting harmful microbes in *Drosophila*. Cell 151:1345–1357

Stern VM, Smith RF, Van Den Bosch R, Hagen KS (1959) The integrated control concept. Hilgardia 29:81–101

The European Parliament and the council of the European Union (2009) DIRECTIVE 2009/128/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 21 October 2009 establishing a framework for community action to achieve the sustainable use of pesticides. Official Journal of the European Union L 309/71. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:309:0071:0086:en:PDF

Vogt H, Baufeld P, Gross J, Köppler K, Hoffmann C (2012) *Drosophila suzukii*: eine neue Bedrohung für den Europäischen Obst- und Weinbau. Bericht über eine internationale Tagung in Trient, 2. Dezember 2011. J Kulturpfla 64:68–72

Wallingford AK, Hesler SP, Cha DH, Loeb GM (2015) Behavioral response of spotted-wing drosophila, *Drosophila suzukii* Matsumura, to aversive odors and a potential oviposition deterrent in the field. Pest Man Sci. doi:10.1002/ps.4040

Weintraub PG, Gross J (2013) Capturing insect vectors of phytoplasmas. In: Dickinson MJ, Hodgetts J (eds) Phytoplasma: methods and protocols, vol 938, Methods in molecular biology. Springer, New York, pp 61–72

Welter SC, Pickel C, Millar J, Cave F, Van Steenwyk RA, Dunley J (2005) Pheromone mating disruption offers selective management options for key pests. Calif Agric 59:16–22

Wise JC (2016) Enhancing resistance management and performance of biorational insecticides with novel delivery systems in tree fruit IPM. In: Horowitz AR, Ishaaya I (eds) Advances in insect control and resistance management. Springer, Cham

Wise JC, Whalon M (2009) A systems approach to IPM integration, ecological assessment and resistance management in tree fruit orchards. In: Ishaaya I, Horowitz AR (eds) Biorational control of arthropod pests: application and resistance management. Springer, Dordrecht, pp 325–345

Witzgall P, Kirsch P, Cork A (2010) Sex pheromones and their impact on pest management. J Chem Ecol 36:80–100