1 Management of Crops to Prevent Pest Outbreaks

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Introduction

Organic farmers face the same potentially severe pest problems as their colleagues in integrated pest management (IPM) and conventional farming systems. However, approaches to manage the pest insects are different because the aim of organic farming is a holistic system perspective rather than simple reductionist control approaches. Organic cropping systems are designed to prevent damaging levels of pests, thus minimizing the need for direct and curative pest control (Peacock and Norton, 1990). Within this chapter, we will briefly explain the standards for organic farming, which also set the framework for pest control. We present a conceptual model for pest control in organic farming and describe the influence of functional agrobiodiversity and conservation biological control on pest management. We focus on the use of preventive strategies and cultural control methods. The system approach is illustrated with examples in organic *Brassica* vegetable and oilseed rape production, because these economically important crops (Ahuja *et al.*, 2010) are attacked by a broad range of different pest insects (Smukler *et al.*, 2008; Ahuja *et al.*, 2010) and show different levels of tolerance. Economic thresholds for pests on oilseed rape are usually higher than on vegetables. Therefore, less control is used in oilseed rape which might lead to the build-up of large pest populations, threatening nearby vegetable fields. With the increasing area of oilseed rape production, pest problems in these crops are likely to increase.

Standards for Organic and IPM Production: Similarities and Differences

Organic farming

Organic farming is regulated by international and national organic production standards, such as the IFOAM (International Federation of Organic Agriculture Movements) Norms (IFOAM, 2012), *Codex Alimentarius* (FAO and WHO, 2007), or European Union (EU) regulation (EC, 2007). Organic standards all have the same principal norms for plant production as described in the *Codex Alimentarius*:

> Organic agriculture is a holistic production management system which promotes and enhances agroecosystem health, including biodiversity, biological cycles, and soil biological activity. It emphasizes the use of

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management practices in preference to the use of off-farm inputs, taking into account that regional conditions require locally adapted systems. This is accomplished by using, where possible, cultural, biological, biotechnical, physical and mechanical methods, as opposed to using synthetic materials, to fulfil any specific function within the system.

(FAO and WHO, 2007)

Thus, the maintenance of plant health primarily relies on preventative measures, such as: (i) the choice of appropriate species and varieties resistant to pests and diseases; (ii) appropriate crop rotations, cultivation techniques, mechanical and physical methods; and (iii) the protection of natural enemies of pests. In the case of an established threat to a crop, plant protection products may only be used if they have been authorized for use in organic production. Within the EU, products authorized for organic farming are listed in Annex II of the implementation rule 889/2008 (EC, 2008). Substances used for plant protection should be of plant, animal, microbial or mineral origin. Genetically modified organisms (GMOs) and products produced from or by GMOs, as well as mineral nitrogen fertilizers are not allowed. Chemically synthesized products are only allowed if they are not available in sufficient quantities in their natural form (e.g. pheromones) and if conditions for their use do not result in contact of the product with the edible parts of the crop (e.g. application in dispensers).

IPM

IPM standards were developed and defined by the International Organisation for Biological and Integrated Control (IOBC) (Boller *et al.*, 2004). With the Sustainable Use Directive (EC, 2009), IPM has become the main part of the European crop protection policy. Central goals of IPM are the prevention and suppression of harmful organisms, as well as the preference of non-chemical methods with few side effects on non-targets (Kogan, 1998). In addition, monitoring of pest insects, economic action thresholds and anti-resistance

strategies are centrepieces of IPM strategies. Nevertheless, pest management in IPM is still dominated by the use of synthetic pesticides. In particular the strong focus on economic thresholds leads to a reductionist view of the systems (El-Wakeil, 2010). Environmental considerations and the presence or absence of beneficial insects are mostly not included in the economic thresholds (El-Wakeil, 2010). According to Ehler (2006), this perpetuates a 'quick-fix mentality', where symptoms are treated instead of causes. IPM principles are only reluctantly implemented by the farmers due to higher costs, and higher risk of failures of non-chemical control methods, as well as lack of experience with these methods (Gruys, 1982). Incentives for farmers to use alternative methods are missing, because the advantage of using sustainable and preventive measures 'is at the social and environmental level and on the long-term, rather than at the private economic level and on the short-term' (Gruys, 1982). In addition, the low price for synthetic pesticides does not reflect the true ecological costs. Thus, for the individual farmer it is often more economical to use a curative pesticide instead of preventive measures. The use of pesticides is more regulated in organic farming systems: only naturally derived substances are allowed. As availability and efficacy of these substances is limited and most of them are considerably more expensive than synthetic pesticides, organic farmers have a stronger incentive to consequently apply preventive measures.

Conceptual Model for Pest Management in Organic Farming

A conceptual model for pest management in organic farming (Fig. 1.1) was proposed by Wyss *et al.* (2005), refined by Zehnder *et al.* (2007) and complemented by Luka (2012, cited in Forster *et al.*, 2013). The fundamental first step of this holistic approach is the benefits of nature conservation measures: ecosystem diversity is increased through habitat management, extensification of land uses, establishment of non-crop habitats and biotope
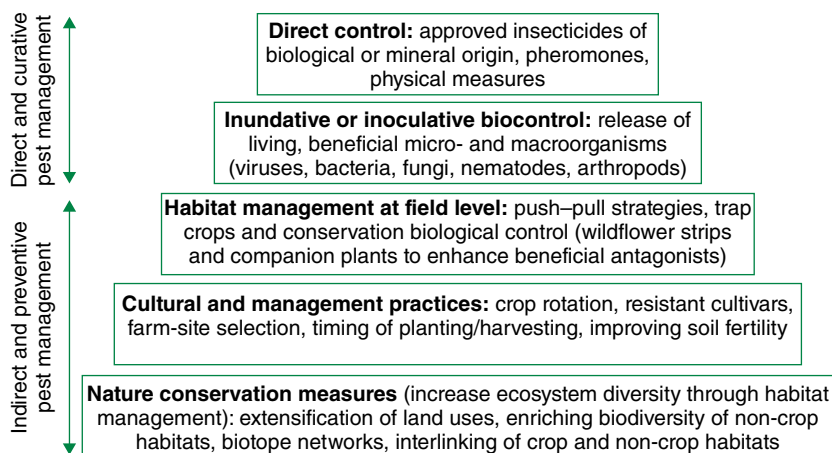
Direct and curative pest management

Indirect and preventive pest management

Direct control: approved insecticides of biological or mineral origin, pheromones, physical measures

Inundative or inoculative biocontrol: release of living, beneficial micro- and macroorganisms (viruses, bacteria, fungi, nematodes, arthropods)

Habitat management at field level: push–pull strategies, trap crops and conservation biological control (wildflower strips and companion plants to enhance beneficial antagonists)

Cultural and management practices: crop rotation, resistant cultivars, farm-site selection, timing of planting/harvesting, improving soil fertility

Nature conservation measures (increase ecosystem diversity through habitat management): extensification of land uses, enriching biodiversity of non-crop habitats, biotope networks, interlinking of crop and non-crop habitats

Fig. 1.1. Conceptual model for pest management in organic farming. (Adapted and supplemented based on Luka, 2012, cited in: Wyss *et al.*, 2005; Zehnder *et al.*, 2007; Forster *et al.*, 2013.)

networks. The second step of the pyramidal model are cultural practices applied by the farmers in order to avoid pest damage (Peacock and Norton, 1990). These practices include crop rotation, increasing crop diversity, timely planting and harvesting, transplanting, weed management, choice of resistant varieties and avoiding areas with high pest presence on the farm level. These practices go hand in hand with the third step which is habitat management at the field level (i.e. companion plants, tailored wildflower strips, push–pull strategies) which aims at interlinking crop and non-crop habitats. These first three steps create a broad and solid basis for healthy plant development. Direct control methods based on biocontrol organisms or bioinsecticides are the fourth and fifth steps of the model. However, these methods can have side effects on beneficial arthropods and thus adversely affect ecosystem services needed for pest prevention. Thus, direct control measures should only be applied in case of threatening pest outbreaks and selective methods should be preferred. The use of non-selective biopesticides should be limited to a minimum. Within this chapter we will focus on the use of preventive strategies (the first three steps in the multi-level model). The last two steps (biocontrol and organically approved insecticides) are only briefly mentioned here and

discussed in detail in Chapters 2 and 3 of this volume, respectively.

Nature Conservation Measures: the Basis for Biodiversity and Ecosystem Services

According to the *Convention on Biological Diversity* of Rio de Janeiro in 1992, biodiversity encompasses the variety of life on earth ranging from genes, through species, to entire ecosystems (United Nations, 1992). Ecosystem diversity covers the diversity of habitats or patches within a landscape and includes the diversity of farming systems, ratio of arable land to other land uses as well as interactions between agricultural land and nearby natural biotopes. Ecosystem diversity and diversified cropping systems have a range of benefits, both short term (e.g. by increase in crop yield and quality due to improved pest control) and long term (e.g. by re-establishing agroecosystem sustainability), on the agronomic level (e.g. biotic and abiotic stress resistance, production of cultivated ecosystems), as well as on the societal and ecological level (e.g. by landscape aesthetics, water and soil quality and flora and fauna conservation, including endangered species, existence of typical habitats with particular species) (Clergue *et al.*, 2009; Malézieux *et al.*, 2009).

Integrating biodiversity conservation into production systems

Agricultural ecosystems comprise productive areas (managed fields), as well as semi-natural and natural habitats (Moonen and Bàrberi, 2008). The productive areas can have a negative impact on biodiversity: monocultures treated with broad-spectrum pesticides to prevent pest outbreaks (Landis *et al.*, 2000) decrease the natural enemies' diversity, reduce species richness, abundance and effectiveness (Naranjo and Ellsworth, 2009; Winqvist *et al.*, 2012). This can start a negative loop where the decrease in the natural enemy populations is followed by an increase in pest populations which necessitate an increase in pesticide applications, which once again negatively impact natural enemy populations (Sandhu *et al.*, 2008; Geiger *et al.*, 2010; Krauss *et al.*, 2011). This negative loop, where practical protection of the rapeseed yield also ensures the highest possible pest population of *Meligethes aeneus* (Fabricius) for the next year, has been described by Hokkanen (2000). Contrary to productive areas, semi-natural and natural habitats are expected to have a positive impact on biodiversity which also benefit the productive areas, for example through biological control or pollination (Sandhu *et al.*, 2008). The *Millennium Ecosystem Assessment* (World Resources Institute, 2005) distinguishes the following ecosystem functions: (i) supporting services; (ii) provisioning services (e.g. food, pollination); (iii) regulating services (e.g. pest and disease control); and (vi) cultural services. The value of ecosystem services to agriculture is enormous and often underappreciated (Tscharntke *et al.*, 2012; Power, 2014). The consequent use of functional agrobiodiversity might not only break the negative loop but even induce a positive loop (Krauss *et al.*, 2011) where reduction of pesticides leads to an increase in antagonists which in turn leads to further reductions of pesticides.

However, there is still a debate how to integrate biodiversity conservation into production systems and how to best achieve the multiple objectives in agriculture. Balmford *et al.* (2012) describe the two main approaches, land sharing and land sparing. Ecosystem schemes in most European countries (EC, 2005) aim at conserving and promoting general biodiversity in order to mitigate the adverse impact of intense farming on nature (Aviron *et al.*, 2009; Birrer *et al.*, 2014). This 'land-sparing concept' implies that biodiversity is functionally negligible for production systems (Tscharntke *et al.*, 2012). In addition, there is limited interaction between conservation practitioners and agronomists which leads to a large gap in translation of ecosystem services into economical yield increase (Letourneau and Bothwell, 2008; Shanker *et al.*, 2012). Other ecosystem schemes directly aim at shaping and influencing biodiversity within the productive area ('land-sharing concept') with the purpose of providing ecological functions which positively influence agricultural production (functional agrobiodiversity) (Ratnadass *et al.*, 2012; Balmer *et al.*, 2013, 2014). Herzog and Schüepp (2013) underlined the value of nature reserves for the protection of highly sensitive species (land sparing), but also pointed out the relevance of semi-natural habits within production fields (land sharing). With the promotion of outcome-oriented agri-environmental schemes being common in agricultural policy, the implementation of nature conservation measures may be supported (Birrer *et al.*, 2014). Outcome-oriented agri-environmental schemes are directly bound to the outcome of a desired ecosystem service in contrast to action-oriented agri-environmental schemes which prescribe a defined set of management actions (Derissen and Quaas, 2013). Such schemes provide more flexibility for land management decisions and underline the importance of the integration of farmers in nature conservation measures (Birrer *et al.*, 2014).

Influence of landscape complexity and farming system

Structurally complex landscapes with a high plant diversity maintain and preserve high levels of arthropod species and provide a spillover of these species towards

crop fields (Molina *et al.*, 2014). Many studies show that herbivore density and crop damage decreases with increasing proportions of non-crop habitats in the landscape (Wezel *et al.*, 2014). Heterogeneous landscapes can sustain higher parasitoid densities than homogeneous production areas (Landis *et al.*, 2000; Tscharntke *et al.*, 2007; Chaplin-Kramer *et al.*, 2011; Rusch *et al.*, 2012). In complex landscapes, higher parasitism rates of pollen beetle *M. aeneus* and lower crop damage were observed than in simple landscapes (Thies and Tscharntke, 1999). Predation and parasitism of *Mamestra brassicae* (Linnaeus) were also found to be related to landscape variables (Bianchi *et al.*, 2005). Interlinking biotope networks with crop and non-crop habitats has a positive effect on abundance and diversity of epigeic predators, such as carabid beetles or spiders, or birds (Pfiffner and Luka, 2000; Östman *et al.*, 2001; Weibull *et al.*, 2003). Approaches to manage non-production areas to create a more biodiverse set of habitats and greater landscape heterogeneity and finally to increase ecosystem services are used by farmers in the USA ('farmscaping'): habitat enhancement through farmscaping increased both biodiversity (particularly plants) and multiple ecosystem functions of agricultural interest (Smukler *et al.*, 2010).

The positive effect of a complex landscape is reinforced by organic farming practices (Östman *et al.*, 2001; Pfiffner and Luka, 2003; Winqvist *et al.*, 2011, 2012): differences in farm structure, pesticide and fertilization regimes, rotations, historical removal of particular landscape elements and differing management strategies (MacFadyen *et al.*, 2009; Puech *et al.*, 2014) result in an increase in conservation biological control on organic farms and a subsequently reduced pest incidence (Östman *et al.*, 2001; Birkhofer *et al.*, 2008; Crowder *et al.*, 2010; Meyling *et al.*, 2013). In particular, the ban of herbicides on organic farms leads to a higher weed biodiversity compared with conventional farms, which also alters species richness and food-web structure (Pfiffner and Luka, 2003; MacFadyen *et al.*, 2009). Organic farming fosters biodiversity of birds, mammals, invertebrates, arable flora (Hole *et al.*, 2005), microbial and faunal decomposers (Birkhofer *et al.*, 2008), and especially beneficial arthropods (MacFadyen *et al.*, 2009; Gomiero *et al.*, 2011; Krauss *et al.*, 2011; Puech *et al.*, 2014) such as spiders and carabid beetles (Pfiffner and Luka, 2003) or parasitoid wasps (MacFadyen *et al.*, 2009). According to Nentwig (2003), a combination of organic farming and semi-natural habitats is important for the conservation and enhancement of species-rich assemblages in an agricultural landscape. Thus, organic farms are harbouring a treasure of high biodiversity and should take special care to conserve it. The preservation and transmission of traditional ecological knowledge is therefore of key importance (Berkes *et al.*, 2000).

Influence of Organic Farming Practices on Abundance of Pest Insects and their Antagonists

Farming practices and cropping systems have their roots in traditional farming and are among the oldest techniques for pest, disease, weed and soil fertility management. They need to be adapted to crops, local climate and soil conditions. Cropping systems – in conventional as well as in organic farming – range from large-scale commercial production in monocultures to highly diversified intercropping systems of subsistence farming (Bajawa and Kogan, 2004). Applied cultural practices therefore vary among different cropping systems. Cultural control practices aim at prevention, avoidance or suppression of pests by creating conditions that are detrimental to the pest or favourable to natural enemies (Hill, 2014). Optimal and expedient implementation of cultural practices requires in-depth knowledge of pest biology and careful long-term planning. Bajawa and Kogan (2004) give a very comprehensive overview on cultural practices for pest control which include: (i) crop rotation; (ii) sanitation; (iii) the use of healthy seed and planting material; (iv) the choice of adapted/resistant/tolerant cultivars; (v) agronomic measures aimed at soil quality and functioning (minimum tillage, animal and

green manure, compost); (vi) agronomic measures favouring healthy plant development (irrigation, optimal nutrition, weed management, row spacing); and (vii) adapted timing for planting or harvest in order to disrupt the crop–pest phenological synchrony. Farming practices, such as crop rotation, soil cultivation and fertilization, also have an effect on below-ground functional biodiversity: Differences in rhizobia strains associated with soybean plants were shown to influence honeydew composition of aphids feeding on those plants (Whitaker *et al.*, 2014). This altered honeydew composition can in turn influence the whole above-ground food web of aphid antagonists and mutualists.

Crop rotation

The yield-stabilizing effect of crop rotation has been known for thousands of years: it was practised during the Han dynasty of China, as well as by the Romans and Greeks (Karlen *et al.*, 1994). Many factors, processes and mechanisms contribute to the yield-stabilizing effect of crop rotations: influence of crop rotation on biotic and abiotic soil properties seem most important, but effects on weed control, soil-borne diseases or decreased insect pressure are also contributing factors (Karlen *et al.*, 1994). Crop rotation drastically changes the above and below ground environment and thus increases temporal diversity in an agricultural landscape which again promotes biodiversity. In organic farming, a diverse crop rotation is still a standard cultural practice and an essential part of organic philosophy. Crop rotation for pest control is useful against pests which have a narrow host range and a limited dispersal ability (Karlen *et al.*, 1994). For instance, maize rootworm (*Diabrotica* spp.) is efficiently controlled by a 3-year rotation (Francis and Porter, 2011). Crop rotation and isolation is also an important control method for the cabbage pest *Contarinia nasturtii* (Kieffer), which overwinters in the soil of the previous crop and migrates less than 100 m. In addition, there are indirect effects of crop rotation on pest incidence:

legumes in a crop rotation are an important source of nitrogen and nitrogen availability influences susceptibility of plants to pest damage.

Fertilization

Level and source of nitrogen fertilization also have an effect on pest abundance and can promote crop-plant resistance to insect pests (Culliney and Pimentel, 1986) as well as tri-trophic interactions (Banfield-Zanin *et al.*, 2012). In cabbage production, lower densities of flea beetles, aphids and caterpillars were observed on organically manured plants compared with chemically fertilized and unfertilized plants (Culliney and Pimentel, 1986; Arancon *et al.*, 2005). Data indicate that leaf nitrogen, water content, glucosinolate content and plant size may have influenced insect populations (Eigenbrode and Pimentel, 1988; Staley *et al.*, 2009). Glucosinolates content in plants can also affect higher trophic levels, due to reduced host quality and because specialist herbivores may use glucosinolates for their own defence (Hopkins *et al.*, 2009). This might also be one explanation for the observations of Stafford *et al.* (2012) who found that specialist cabbage aphid, *Brevicoryne brassicae* (Linnaeus) performed better on organically fertilized cabbage plants, whereas the generalist green peach aphid, *Myzus persicae* (Sulzer) had a lower performance on organically fertilized plants. Positive effects of organic fertilization were also observed in other crops: in potato production, Colorado potato beetle densities were lower in organically manured fields due to altered mineral content of potato leaves (Alyokhin *et al.*, 2005). Synthetic fertilizers were found to increase sap-feeding insects (aphids, mites, whiteflies) due to increased availability of nitrogen (Garratt *et al.*, 2011). Tri-trophic interactions are also influenced by source of nitrogen: in a meta-analysis, Garratt *et al.* (2011) showed a significant positive effect of organic fertilizers on natural enemy responses. Similar results were obtained by Banfield-Zanin *et al.* (2012), who observed that mortality of

ladybird beetle larvae was 10% higher if they fed on aphids on conventionally fertilized compared with aphids on organically fertilized *Brassica* plants. Thus, in organic farming systems, natural enemies may have a higher efficacy than in conventional farming systems. The positive impact of organic fertilizers on natural enemies might be one factor explaining the higher number of natural enemies observed in organic systems (Garratt *et al.*, 2011). Even though higher yields might be possible using mineral fertilizers, this comes at the cost of higher insect levels which necessitate insecticide applications. In view of a system approach, the ban of mineral fertilizers in organic farming seems appropriate. However, it is sometimes challenging for organic farmers to synchronize soil nutrient supply and release in the rhizosphere with the crop nutrient demand (Dorais, 2007), especially if cultivars bred under and adapted for conventional conditions are used.

Tillage and soil cultivation

Minimum tillage is an agronomic measure aimed at soil quality and functioning (Gadermaier *et al.*, 2012). Reduced tillage and organic farming practices have synergistic positive effects on soil biota (Kuntz *et al.*, 2013). Minimum tillage and no tillage (direct seeding) help to reduce erosion, subsoil compaction, nitrate leaching to groundwater, and energy consumption, while increasing soil biota activity, soil organic matter, and thus carbon sequestration (Dorais, 2007; Palm *et al.*, 2014; Wezel *et al.*, 2014). High organic matter and an active soil biology are essential for good soil fertility. Crops growing in these conditions generally show lower abundance of several insect herbivores (Altieri and Nicholls, 2003). Phelan *et al.* (1995) showed that females of European corn borer, *Ostrinia nubilalis* (Hübner) preferred plants in conventional soil for oviposition. Thus, soil-management practices can significantly affect the susceptibility of crops to pests (Lenardis *et al.*, 2014). While minimum tillage seems preferable based on soil quality and pest

susceptibility, tillage is often necessary for weed control as well as to accelerate decomposition of crop residues (Dorais, 2007). The destruction of cabbage roots and harvest residues immediately after harvest is a key method to prevent pupation of cabbage root fly larvae, *Delia radicum* (Linnaeus) or lepidopteran pests (*M. brassicae*, *Plutella xylostella* (Linnaeus), *Pieris* sp.). Soil cultivation after harvest and removal of volunteer oilseed rape plants is important to reduce population levels of swede midge (*C. nasturtii*), especially in regions were oilseed rape is grown in close vicinity to production of *Brassica* vegetables. In addition, soil cultivation reduces the risk of diseases that survive on infected debris such as phoma stem canker and light leaf spot. However, there is clearly a conflict of strategies: no tillage is recommended to avoid the spread of clubroot, another major oilseed rape disease, as well as to protect parasitoids of pollen beetles which overwinter as pupae in the soil of previous oilseed rape fields and which are destroyed by ploughing (Nilsson, 2010). All soil cultivation measures (ploughing, non-inversion tillage, superficial soil loosening, mechanical weed control and grass cutting) potentially disturb epigeic predators and lead to an increased mortality and emigration of these insects. Spiders were found to be most vulnerable, but carabid and staphylinid beetles were also reduced (Kromp, 1999; Thorbek and Bilde, 2004; Legrand *et al.*, 2011). However, mechanical weed control in organic farming doesn't perturb the flora like herbicide-using farming systems, which generally leads to a higher weed density and diversity on organic farms. The increased weed density was shown to have a positive effect on carabid beetles in organic wheat fields (Diehl *et al.*, 2012). In addition, a higher weed density interferes with host plant location of specialized pest insects such as *D. radicum*: plants in bare soil are more heavily attacked than plants growing in diverse backgrounds (Finch and Collier, 2000). Thus, possible positive and negative effects of tillage and soil cultivation require a balanced decision based on the observed situation and pest pressure in the field. Potentially negative effects of soil cultivation

can be mitigated by refuge areas adjacent to fields and by maintaining crop and landscape diversity.

Host plant resistance/cultivar choice

Cultivar choice has a huge impact on the outbreak of insect pests. However, first criteria for cultivar choice are often market demands and product quality (appearance, taste, nutritional value and health compounds, shelf life and shipping tolerance) (Dorais, 2007). The second criterion is often the resistance to plant pathogens. Pest insect resistance or tolerance usually only play a subordinate role for cultivar choice and is rarely addressed in breeding programmes. This can be partly explained by the fact that pest attacks often occur infrequently and artificial infestation (as often applied in disease screening) is often too time-consuming. Moreover, the plant reaction to pest attack is influenced by very complex interactions and often inherited in a quantitative manner. In general, partial resistance or tolerance might be more effective in the long term than complete resistance, because tolerant cultivars pose a lower selection pressure on pests for forming adapted biotypes (van Emden, 1991) and they can support a certain level of pests and thus maintain antagonist activity. In *Brassica* vegetables and oilseed rape, glucosinolates are produced in the leaves and play a major role in insect–plant interactions (Giamoustaris and Mithen, 1995; Hopkins *et al.*, 2009). Huge differences in glucosinolate content are observed between different cultivars. While high levels of glucosinolates serve as a feeding deterrent for generalist herbivores, they often act as a feeding attractant for specialized herbivores and their predators or parasitoids (Hopkins *et al.*, 2009). Other traits like leaf colour, thickness of wax layer or wax composition can influence susceptibility to pest attack and be used for indirect selection. Voorrips *et al.* (2008) could show that tolerance of cabbage to thrips was related to earliness, Brix and leaf surface wax. In contrast, higher levels of damage caused by lepidopteran pests were reported for *Brassica* genotypes with light green leaves and a reduced wax layer (Eigenbrode and Espelie, 1995). A strong selection for pest tolerance or resistance could result in unintended changes in flavour and taste. In many cases, even more complex defence mechanisms and chemical cues are mediating insect–plant interactions (Bottrell *et al.*, 1998): semiochemicals emitted by plants after damage by herbivores can directly affect the herbivores due to toxic or repellent properties as well as indirectly by attracting natural enemies (Simpson *et al.*, 2013). In addition they can also act as plant-to-plant signals, warning their neighbouring plants. In a comprehensive review, Cortesero *et al.* (2000) summarizes how 'plant attributes influence natural enemy efficiency by providing shelter, mediating host/prey accessibility, providing host/prey finding cues, influencing host/prey suitability, mediating host/prey availability, and providing supplemental food sources for natural enemies'. However, the active contribution of plants for the efficacy of natural enemies has rarely been addressed in breeding programmes. Breeding for conventional farming focuses on increasing the yield under optimized conditions with large external inputs of fertilizers and pesticides which can result in loss of ability to attract natural enemies. This was shown by Degenhardt *et al.* (2009) for maize varieties: modern North American varieties have lost the ability to emit (*E*)-β-caryophyllene which attracts entomopathogenic nematodes that infect and kill the western corn rootworm. Thus, these varieties receive little protection from the nematodes. Currently, organic farming still largely depends on varieties bred by conventional breeders (Lammerts van Bueren *et al.*, 2002). Varieties that fit in the system perspective of organic farming are still lacking. This is a very vulnerable point of the whole system approach. Plant traits especially important for organic farming systems include: (i) adaptation to organic fertilization and crop protection; (ii) a better root system; (iii) ability to interact with beneficial soil microorganisms; (iv) the ability to suppress weeds; and (v) the ability to tolerate pests and diseases (Lammerts van Bueren *et al.*, 2002). Unravelling the underlying genetic and

physiological mechanisms for pest tolerance is just at the beginning. Broekgaarden *et al.* (2010) tested two cabbage cultivars for their herbivore community composition throughout the season and found significant differences in resistance level which could be attributed to a high level of RNA expression of potential defence genes. Jyoti *et al.* (2001) tested wild-crop relatives in order to identify genetic resources with improved tolerance against cabbage maggot. Breeding programmes focusing on these traits are urgently needed to fill this gap in the whole system approach. In addition, different cultivar types might be considered for efficient pest control: Instead of cultivating homogeneous F_1 hybrids, open-pollinated populations or cultivar mixtures with different traits and tolerance levels against various pests might be a promising strategy.

Other agronomic measures

Other different agronomic measures are used in order to reduce or avoid pest damage. Certified seed and planting material are a prerequisite for healthy plant development. Adapted timing for planting or harvest can disrupt the crop–pest phenological synchrony: in areas with high pressure of swede midge (*C. nasturtii*), broccoli is produced mainly in spring and autumn instead of summer. During summer, cauliflower, which is less susceptible to swede midge, is produced as a substitute. Damage by autumn oilseed rape pests, such as flea beetles, *Psylloides chrysocephala* (Linnaeus) or *Athalia rosae* (Linnaeus) is diminished by early sowing and by creating conditions favourable for rapid plant development. Measures to create favourable growing conditions and healthy plant development include adjusted irrigation, drainage, optimal nutrition, weed management, or adapted row spacing. Overhead irrigation during evening hours instead of drip irrigation was shown to reduce infestation with *P. xylostella* by more than 85% (McHugh and Foster, 1995), but this strategy is only possible in areas with low pressure of fungal diseases. Increased irrigation – overhead or drip irrigation – can also mitigate damage

caused by flea beetles whereas a reduction in irrigation can reduce damage of cabbage fly *D. radicum* because its eggs are highly sensitive to drought. Thus, an overall pest and disease risk assessment is necessary to select suitable agronomic measures for pest prevention. As cultural practices can have opposing effects on different pests and diseases, they need to be adapted according to local pest and disease pressure. This requires a lot of attention and knowledge of the farmers. Adapted cultural practices can also stimulate compensatory plant growth after pest infestation: in cabbage production, seedlings are planted deeper and are earthed up after transplanting in order to stimulate secondary root growth to compensate for damage caused by *D. radicum*. In oilseed rape, favourable growing conditions can stimulate compensatory growth of side shoots after bud damage by pollen beetle (*M. aeneus*) on the main shoot. This can even result in an overcompensation leading to higher yields in fields with moderate pollen beetle incidence compared with fields with low or no pollen beetle incidence (Wahmhoff, 2000). Mechanical weed control can also reduce pest incidence: in oilseed rape hoeing in autumn reduces not only the weeds but also removes the oldest oilseed rape leaves with the highest infestation of flea beetle larvae from the plants (Wahmhoff, 2000). Hoeing in spring has a positive effect on soil temperature and thus on nitrogen mineralization which creates favourable conditions for compensatory growth after pollen beetle infestations (Wahmhoff, 2000). In cabbage production, machines for mechanical weed control can reduce damage by *D. radicum* to a certain extent. Since cultural control practices do not result in eradication of pest insects, they allow the conservation of natural enemies.

Habitat Management at Field Level

The cultivation of crop plants necessarily leads to a simplification of nature's biodiversity and creates artificial ecosystems which need constant human interventions (Altieri, 2007). Habitat management at field

level restores a certain level of biodiversity within crop fields and aims at creating conditions favourable to natural enemies (conservation biological control) or detrimental to the pest (push–pull strategy). Apart from positive effects on pest control, habitat management at field level can also improve other ecosystem functions, such as weed control, mitigation of soil erosion, and nutrient cycling (e.g. by fixing atmospheric nitrogen in legume plants) (Simpson *et al.*, 2013).

A vast variety of measures and strategies are used for habitat management at field level (Malézieux *et al.*, 2009; Parolin *et al.*, 2012), for example:

- Intercropping and mixed cropping stands for the simultaneous growing of different harvested crop species in one field.
- Under-sowing crops, often clover, are sown with or after the main crop and are not harvested; their most intensive growth occurs before covering by the main crop or after harvest of the main crop.
- Companion plants are non-crop plants grown within the fields for different purposes: (i) attraction and maintenance of natural enemies by providing pollen and nectar (insectary plants); (ii) repellence and/or interception pest insects (repellent plants); and (iii) influence on nutrition and/or chemical defence of the crop plants (Parolin *et al.*, 2012).
- Banker plants, mainly used in greenhouse production, are a mini-rearing system for natural enemies (Huang *et al.*, 2011). The banker plants supply a non-pest prey (e.g. aphids which infest the banker plant but not the crop plant) and thus sustain the natural enemies within the greenhouse.
- Beetle banks – grass-covered earth banks in the middle of the field – are shelter habitats which provide suitable overwintering sites for predatory carabid and staphylinid beetles or spiders (Jonsson *et al.*, 2008).
- Cover crops are sown after harvest of the main crop before sowing of the new crop mainly to prevent nitrogen leaching and soil erosion.

- Flowering strips usually consist of insectary plants sown at field margins and are aimed to attract natural enemies by providing food and shelter.
- Barrier plants are also sown at field margins and are aimed at intercepting immigrating pest insects (Parolin *et al.*, 2012).
- Trap crops or trap plants are of a preferred growth stage, cultivar or species and thus attract, divert, intercept and/or retain targeted insects because they are more attractive than the main crop (Parolin *et al.*, 2012). Trap crops serve as a sink for insects, preventing the movement of insects to the main crop (Shelton and Nault, 2004). Dead-end trap crops are plants highly attractive to insects, but unsuitable for their reproduction (Shelton and Badenes-Perez, 2006).

All these approaches are applied in different combinations to address different pest problems. A maximum of spatial diversity is created in permaculture or agroforestry with the idea to confront pests with a diverse array of non-host vegetation and thus prevent build-up of pest populations (Francis and Porter, 2011).

Intercropping and cover cropping

In cabbage production, intercropping and cover cropping is implemented as an efficient strategy for *D. radicum* prevention: oviposition of *D. radicum* is significantly reduced in cabbage fields intercropped with clover, because non-host plants interfere with host-plant location of this specialist cabbage pest (Finch and Collier, 2000; Meyling *et al.*, 2013). Reduced pest attacks were reported for cabbage intercropped with onion or tomato (Asare-Bediako *et al.*, 2010). Disruption of host location resulted from the green leaves of the non-host plants, and not from their odours and/or tastes (Finch *et al.*, 2003). The higher weed density observed in organic farming can have a similar effect: plants in bare soil are more heavily attacked by specialist insect pests than plants growing in diverse backgrounds (Finch and Collier,

2000). Similar observations were made by Andow *et al.* (1986) for the specialist cabbage pests *Phyllotreta cruciferae* (Goeze) and *B. brassicae*: cabbage growing in living mulches resulted in lower pest populations than cabbage growing in bare soil. Cover cropping also provides habitat refuges for predators between seasons until the time of cabbage establishment. In addition cover crops prevent soil erosion and help to control weed problems.

Push–pull strategy

This strategy is based on the behavioural manipulation of pest insects: repellent or deterrent companion or intercrop plants within the field 'push' the pest insect from the crop and attractive trap crop plants around the field 'pull' them from the crop (Cook *et al.*, 2007; Khan *et al.*, 2010; Ratnadass *et al.*, 2012). The most important example of a successful application of the push–pull strategy is the stem borer management developed by the International Centre of Insect Physiology and Ecology for African subsistence maize and sorghum production (Khan *et al.*, 2010): Napier grass, (*Pennisetum purpureum* Schumach.) and Sudan grass (*Sorghum vulgare* Pers. var. *sudanense* Hitchc.) are highly attractive for egg laying and pull adult pest insects away from the main crop. At the same time, larval development of the stem borer is very poor in Napier grass, resulting in low survival rates. Legumes of the genus *Desmodium* and molasses grass (*Melinis minutiflora* P. Beauv.) are used as the push component within the fields. Apart from repelling the stem borer, *Desmodium* also suppresses the main weed *Striga hermonthica* (Delile) Benth. by an allelopathic mechanism and has a positive effect on soil quality, whereas molasses grass increased parasitism of stem borer larvae by *Cotesia sesamiae* (Cameron). The economic benefit from the application of this strategy results from an increase in yield by at least 2 t/ha/year but is also due to the fact that the push and pull plants can be used for animal fodder (Cook *et al.*, 2007; Khan *et al.*, 2010).

Trap crops are an important part of push–pull strategies, but can also be used as a single measure (Hokkanen, 1991). In particular, highly mobile insects which cause damage immediately upon immigration in the field (e.g. flea beetles *Phyllotreta* sp., pollen beetles *M. aeneus* in cabbage and oilseed rape production) are good targets for trap-crop strategies (Shelton and Badenes-Perez, 2006). Turnip rape (*Brassica rapa* Linnaeus) sown as a perimeter trap crop around oilseed rape fields is used as a trap crop for pollen beetles. Due to its advanced growth stage, the olfactory and visual cues of turnip rape plants are more attractive to pollen beetles than oilseed rape plants (Cook *et al.*, 2006). Perimeter turnip rape trap crops can significantly reduce pollen beetle populations in the centre of the oilseed rape fields (Büchi, 1989; Büchs and Katzur, 2004; Cook *et al.*, 2004). Currently, a push–pull strategy for pollen beetle is being developed based on this trap crop in combination with within-field application of repellents: different essential oils, such as lavender oil (Mauchline *et al.*, 2013), lemongrass oil or cornmint oil (Daniel, 2014) were shown to have a repellent effect on pollen beetles, but there are still several open questions concerning formulation and application of these oils. Silicate rock dusts also showed a significant repellent effect on pollen beetles (Daniel *et al.*, 2013), but further research is needed to bring a push–pull strategy for pollen beetle control into practice. Turnip rape trap crops are also used around cauliflower and broccoli fields in order to prevent immigration of pollen beetles from neighbouring oilseed rape fields to cauliflower fields. Because immigration occurs shortly before harvest, the use of insecticides is not possible and trap crops are the only option for control (Hokkanen, 1991).

Conservation biological control

Conservation biological control is another major focus of habitat management at field level. Eilenberg *et al.* (2001) defined conservation biological control as 'Modification of the environment or existing practices to

protect and enhance specific natural enemies or other organisms to reduce the effect of pests'. Many natural enemies depend on non-host food during parts of their life cycle, for example parasitoids of Lepidoptera need nectar as food during the adult life stage. Flowering strips at field margins, with-in-field companion plants, intercropping or cover crops provide plant-based food sources (nectar, pollen), alternative hosts and/or honeydew to the natural enemies (Jonsson *et al.*, 2008). In addition, these structures also provide favourable microclimatic conditions, shelter, habitats for hibernation or aestivation and refuge from disturbance caused by agricultural practices (Jonsson *et al.*, 2008). Many authors have shown the benefits of planting flowers near crop production sites for increasing parasitoid densities (Jervis *et al.*, 1996; Heimpel *et al.*, 2004; Lavandero *et al.*, 2005; Winkler *et al.*, 2006; Bianchi and Wäckers, 2008; Pfiffner *et al.*, 2009). The concept of conservation biological control has been readily accepted and implemented by many organic farmers, because it absolutely coincides with organic farming principles, such as biodiversity and biological cycles, and because it is supported by lower fertilization levels, reduced insecticide applications and a higher tolerance to pest infestations (Simpson *et al.*, 2013). Organic farming practices and conservation biological control thus support each other: for instance Ponti *et al.* (2007) observed that both intercropping with buckwheat and mustard and the use of compost instead of mineral fertilizer decreased abundance of the cabbage aphid *B. brassicae* in broccoli. However, vegetation diversification does not necessarily reduce pest insect incidence, because polyphagous pests are able to use a wide range of host plants (Ratnadass *et al.*, 2012). In addition, intraguild predators might also be enhanced by habitat management and can sometimes disrupt biological control (Straub *et al.*, 2008). However, in the majority of cases, conservation of natural enemy biodiversity and biological control are compatible or even complementary goals (Straub *et al.*, 2008), but in-depth knowledge of the biology and requirements of the pest as well as of the antagonists and

hyperparasitoids is necessary to develop tailored measures of in-field habitat management. Resources that selectively benefit key natural enemies are needed. Within the next section, we present a case study on the development of conservation biological control in Swiss cabbage production.

Case Study: Development of Conservation Biological Control for Swiss Cabbage Production

Different Lepidoptera larvae (*M. brassicae*, *Pieris brassicae* (Linnaeus), *Pieris rapae* (Linnaeus) and *P. xylostella*) are among the key pests of *Brassica* vegetables (Peacock and Norton, 1990; Cartea *et al.*, 2009; Ahuja *et al.*, 2010). As part of the concept on ecological compensation areas, Swiss farmers established 3500 ha of flower strips (Aviron *et al.*, 2009) using seed mixtures of about 25 species (Pfiffner and Wyss, 2004). This approach is very broad, benefitting biodiversity in general, but it is not focused on the species of agronomic interest (Ratnadass *et al.*, 2012). The effects of these species-rich wildflower strips growing next to or in close vicinity to cabbage fields on the parasitation rate of Lepidoptera larvae was monitored in 2001 and 2002 (Pfiffner *et al.*, 2003). The most abundant parasitoid species were *Microplitis mediator* (Haliday) in *M. brassicae*, *Cotesia rubecula* (Marshall) in *P. rapae* and *Diadegma semiclausum* (Helen) in *P. xylostella* (Pfiffner *et al.*, 2003; Lauro *et al.*, 2005). However, the wildflower strips did not consistently improve the control of *P. rapae* and *M. brassicae* (Pfiffner *et al.*, 2009) because only a few of the 24 plant species in the mixture (e.g. *Centaurea cyanus* Linnaeus, *Fagopyrum esculentum* Moench and *Daucus carota* Linnaeus) might have benefitted the target parasitoids. Other authors have shown that flower strips can increase the reproductive lifespan of *Diadegma* sp. (Winkler *et al.*, 2006; Lee and Heimpel, 2008) as well as parasitation rates in neighbouring cabbage fields (Lee and Heimpel, 2005; Lavandero *et al.*, 2006; Winkler *et al.*, 2006, 2009). Thus, an improvement of conservation biological control might be achieved

by targeted selection of flowering species. The most important features of flower species are the attractiveness to parasitoids, nectar accessibility and food quality (Wyss and Pfiffner, 2008).

In order to select plants most suitable for *M. mediator*, several laboratory experiments were conducted: Olfactory attractiveness of five different flowers (bishop's weed *Ammi majus* Linnaeus, cornflower *C. cyanus*, buckwheat *F. esculentum*, candytuft *Iberis amara* Linnaeus, and oregano *Origanum vulgare* Linnaeus) was tested in laboratory Y-tube olfactometer experiments (Belz *et al.*, 2013). *C. cyanus*, *F. esculentum* and *I. amara* were found to be particularly attractive and might therefore be able to recruit *M. mediator*. In addition to a high attractiveness, a suitable flower must also provide accessible nectar in a utilizable quality for the parasitoid. Effects of different nectar sources on fecundity and longevity of *M. mediator* were tested in laboratory experiments (Géneau *et al.*, 2012): nectar from *F. esculentum*, *C. cyanus* and *Vicia sativa* Linnaeus significantly increased fecundity (parasitation rate) and longevity of *M. mediator*, whereas *A. majus* increased only longevity but not fecundity. In addition, *F. esculentum*, *C. cyanus* and *V. sativa* also had a positive effect on longevity of *Diadegma fenestrale* (Holmgren), a generalist parasitoid of lepidopteran pests (Géneau *et al.*, 2012). *F. esculentum* is also known to support *D. semiclausum* (Lavandero *et al.*, 2006). The experiments also showed that *M. mediator* can use the extra-floral nectar of *C. cyanus* and *V. sativa* as a food source (Géneau *et al.*, 2012). The fact that extra-floral nectaries usually produce nectar for a much longer period than floral nectaries makes this two flower species especially interesting for the enhancement of *M. mediator* (Géneau *et al.*, 2012, 2013).

In order to avoid enhancement of the pest insect, the effect of nectar sources on fecundity and longevity of *M. brassicae* was tested in another laboratory experiment: none of the flowers positively influenced fecundity and longevity of *M. brassicae* (Géneau *et al.*, 2012). *P. rapae* is also unlikely to benefit from flowers, because it can

only access nectar from very few plant species: during its flight period under sunny and dry conditions, nectar concentration and viscosity is too high for exploitation by Lepidoptera (Winkler *et al.*, 2009). The contrary is true for *P. xylostella* which is mainly active at dusk when relative humidity is high: all plant species suitable for the parasitoid *D. semiclausum* also benefitted *P. xylostella* (Winkler *et al.*, 2009). Different observations were made by Lavandero *et al.* (2006), who observed *F. esculentum* to selectively benefit *D. semiclausum* but not its host *P. xylostella.*

Based on these experiences, *F. esculentum* and *C. cyanus* have been selected for the composition of a tailored wildflower strip. *V. sativa* and *A. majus* were added to the seed mixture in order to have floral and extra-floral nectar available from the end of May until the end of September. Although *A. majus* does not benefit the parasitoids, it is a valuable plant in the mixture because it ensures a soil covering and weed suppression during the summer, as well as a nectar supply for a broad spectrum of beneficials (e.g. hover flies) (Balmer *et al.*, 2013, 2014). In addition to the tailored wildflower strips, cornflowers (*C. cyanus*) were established as companion plants within the cabbage fields in order to provide nectar in closest vicinity to the hosts. The parasitation of *M. brassicae* larvae by *M. mediator* was significantly higher in the presence of within-field companion plants, whereas the distance to the tailored wildflower strip did not affect parasitation of Lepidoptera larvae (Balmer *et al.*, 2013, 2014). Parasitation of *M. brassicae* eggs was significantly increased in the vicinity of the wildflower strip, whereas within-field companion plants had little influence. Larval parasitoids responded more readily to the provision of nectar resources, because their larger body size enables a target-oriented flight, whereas egg parasitoids cover only short distances by active dispersal (Pfiffner *et al.*, 2009). For the reduction of crop damage, however, egg parasitation and egg predation seems more important than larval parasitation, because parasitized larvae still cause a certain amount of damage. The main egg parasitoid observed in

the experiments was *Telenomus* sp. (Pfiffner *et al.*, 2009; Balmer *et al.*, 2013, 2014). A laboratory mass rearing and subsequent release of this insect (augmentative biological control) seems therefore an interesting approach to further improve the system. The cabbage yield in the field experiments was positively, but not significantly, influenced by the within-field companion plants: the weight per cabbage head was increased by 18% in the presence of cornflowers.

Egg predation was significantly increased by within-field companion plants but remained unaffected by the distance to the tailored wild flower strip (Balmer *et al.*, 2013, 2014). This is contrary to the observations of Pfiffner *et al.* (2009), who observed a higher egg predation in the vicinity of multi-species flower strips. Wildflower strips are known to harbour many epigeic polyphagous arthropods, such as carabid beetles and spiders (Pfiffner and Luka, 2000; Ditner *et al.*, 2013). Within-field companion plants were also able to shift diversity and species composition of epigeic predators resulting in differences compared with cabbage monocultures (Ditner *et al.*, 2013). Less-specific interventions, like a certain level of weeds, is already beneficial for the predator community (Balmer *et al.*, 2013). The stomach contents of captured predators were analysed by molecular gut analyses (Traugott *et al.*, 2006) in order to identify the main prey species: pest Lepidoptera belonged to the prey spectrum, whereas parasitoid DNA was rarely detected in predator guts (Balmer *et al.*, 2013). This indicates that carabids, staphylinids and spiders do not substantially interfere with parasitoid biocontrol. Hyperparasitoids might be another factor disrupting efficient biological control: Lee and Heimpel (2005) observed hyperparasitation of *Diadegma insulare* (Cresson) by *Conura side* (Walker) in field experiments but the presence of buckwheat did not increase hyperparasitism rates.

Thus, every intervention needs to be tailored and adapted to local situations in order to selectively promote the desired antagonist. If crops are attacked by a complex of insect pests, the implementation of trap cropping and tailored conservation biological control becomes more difficult (Shelton and Badenes-Perez, 2006). In these situations, the use of insecticides which control more than one pest and which is less knowledge intensive and less complex based on agronomical manipulations becomes more attractive. As habitat management strategies do not result in a marketable product, such as an insecticide, research funding is often limited (Shelton and Badenes-Perez, 2006). There are still huge gaps in knowledge, because complex interactions between species, environments and management practices are difficult to research in traditional factorial experimental approaches. A system approach in research and an understanding of the dynamic interactions is needed.

Direct Control Measures

The last two steps in the pyramidal model of organic pest control are inundative biological control (mass release of antagonists or application of biocontrol products) and the use of physical control measures, pheromones or approved insecticides (Fig. 1.1). Contrary to cultural practices and implementation of within-field habitat management, the application of biocontrol agents or bioinsecticides provides the farmers with methods for rapid reactions.

Biological control

Biological control agents are described in detail in Chapter 3 of this volume. They are often used in *Brassica* vegetables: the use of *Bacillus thuringiensis* Berliner var. *kurstaki* and *aizawai* is a very effective direct method against lepidopteran larvae without causing side effects on natural enemies. In the cabbage example above, the rearing and mass release of the egg parasitoid *Telenomus* sp. also belongs to the third step of the pyramidal model.

Physical pest control

Physical methods of pest control include nets, fences, particle films or inert dusts

(Vincent *et al.*, 2003). Crop netting is used in cabbage production against *C. nasturtii*, *D. radicum*, Lepidoptera or flea beetles *Phyllotreta* sp. Although this method is highly efficient, it has the disadvantage of excluding natural enemies from the crop. In particular, problems with cabbage whitefly, *Aleurodes proletella* (Linnaeus) can increase under net covering due to missing antagonists. Crop netting also affects disease outbreaks by increasing humidity. In order to avoid this problem, exclusion fences were developed for *C. nasturtii* and *D. radicum*, two very low-flying insects (Vernon and Mackenzie, 1998). Fences of 1.4 m height with an overhang could reduce damage caused by *C. nasturtii* in broccoli and kohlrabi by 78% (Wyss and Daniel, 2004). The use of inert dusts is also considered to be a physical control method. There are many different kinds of inert dusts: lime, common salt, sand, kaolin, paddy husk ash, wood ash, clays, and diatomaceous earths (Vincent *et al.*, 2003). Silicon compounds are used to strengthen plants and to constitute a barrier against insect feeding (Simpson *et al.*, 2013). In addition, silicon compounds can boost plant volatile production after herbivore infestation which attracts natural enemies (Simpson *et al.*, 2013). In oilseed rape production, the good efficacy of inert dusts (i.e. clinoptilolithe) against pollen beetles was shown to increase yield by 23% (Daniel *et al.*, 2013). Kaolin particle film technology has been developed for fruit production (Daniel *et al.*, 2005) but was recently registered for pollen beetle control in Switzerland (Dorn *et al.*, 2014). The use of sounds and vibrations is another physical pest control method, but examples for efficient applications are still rare. Sound traps as a part of an attract-and-kill strategy are used for mole crickets (Parkman and Frank, 1993). Field efficacy of disruptive vibrational signals for mating disruption was demonstrated for the leafhopper, *Scaphoideus titanus* Ball on grapevine plants (Eriksson *et al.*, 2012).

Natural insecticides

Insecticides for organic farming must meet the standards for organic farming and are therefore of natural origin. They are described in detail in Chapter 2 of this volume. In *Brassica* vegetable production, potassium soap, horticultural oils and pyrethrum are used against aphids. Pyrethrum is also applied against flea beetles. Neem can be used against *A. proletella*, but the efficacy is only sufficient if drop-leg technology for under-leaf application is used. Spinosad is used against different Lepidoptera larvae, thrips, *C. nasturtii* and *D. radicum*. Most natural products (pyrethrum, neem oil, rotenone, nicotine) have a long history of use as insecticides (Isman, 2006; Rosell *et al.*, 2008; Gerwick and Sparks, 2014). Their main advantage lies in their lack of persistence and bioaccumulation in the environment, because they generally degrade faster in sunlight, air and moisture than synthetic products (Grdiša and Gršić, 2013). Compared with conventional pesticides, they are usually more selective to non-target insects (Grdiša and Gršić, 2013). However, some insecticides used in organic farming (such as spinosad, pyrethrum and rotenone) can have detrimental side effects on non-target organisms (Jansen *et al.*, 2010). After application of spinosad against *C. nasturtii* or Lepidoptera, side effects on aphid parasitoids often lead to an increase in aphid infestation (Hommes and Herbst, 2014). Parasitoids of Lepidoptera are also negatively influenced. Thus, all efforts to establish conservation biological control can be annihilated. Crop netting against pests can also have this destabilizing effect by excluding antagonists, but side effects of crop netting are more restricted in time and space than the side effects of spinosad. In order to avoid the negative impact of direct control measures on ecosystem functionality, selective methods for pest control should be preferred and the necessity of applications should be carefully assessed. To date, the limiting factors for organic production of *Brassica* vegetables are *C. nasturtii* and *D. radicum* because no efficient preventive control strategy is available which often makes the application of spinosad necessary.

Economic thresholds to determine the necessity of direct interventions in IPM are

often blindly accepted for organic farming systems. However, these thresholds do not reflect the system approach. The presence of antagonists, different fertilization levels, influence of cultivar, and interaction between different pests are not taken into account. In particular, potential negative effects on beneficial insects are missing (i.e. if the treatment of a primary pest leads to extinction of antagonists and thus to the necessity of treatments against secondary pests, a higher economic threshold for the primary pest seems appropriate – from the economic as well as from the ecological point of view). Most economic thresholds are not based on sound experimental data, but are mainly estimations based on expert opinion (El-Wakeil, 2010). In oilseed rape production, the economic threshold for pollen beetle control in the UK is tenfold higher than in Germany or Switzerland (Wahmhoff, 2000). Because of the uncertainties concerning insect population growth rates, most thresholds are rather conservative in order to prevent damage. The challenge of the forthcoming years will be to develop economic thresholds that consider multiple factors but that are still simple to use (El-Wakeil, 2010).

Outlook and Conclusions

According to Francis and Porter (2011), 'Sustainability means preserving economic productivity while taking seriously the ecological foundation and social implications and impacts of farming. It includes designing systems that are resilient and can endure for the indefinite future.' In order to achieve sustainability, the positive impacts of functional agrobiodiversity and of conservation biological control need to be fully exploited. Therefore, agricultural practice needs to be adapted at crucial points: most important is the reduction of non-selective insecticides in order to avoid side effects on beneficial arthropods. This insecticide reduction can only be achieved if robust and adapted cultivars are planted. However, cultivars that fit in the system perspective of organic farming are still lacking which is a very vulnerable point of the whole system approach.

The preventive approach of crop protection requires system-based research, which integrates biological, chemical, physical, ecological, economic and social sciences in a comprehensive way (Lichtfouse *et al.*, 2009) in order to describe relationships and interactions between soil, microorganisms, plants and insects, as well as the influence of agronomic measures on these relationships. Currently research is exploring many interactions, such as plant–microbes–insect, and knowledge is rapidly growing. The challenge in the coming years will be to translate this knowledge into efficient, environmentally safe and economic ways for pest control.

The redesign and development of sustainable cropping systems is very knowledge intensive and requires highly educated and attentive farmers. So far, many farmers are reluctant to change their usual practices, mainly because short-term benefits seem too low and are not easily measurable. As pest problems do not end at farm gates, a closer collaboration between neighbouring farmers could tackle pest problems at a region-wide scale and might increase the impact of conservation biological control and cultural measures. Region-wide control approaches, especially for highly mobile pests, will play a bigger role in future pest control.

Acknowledgements

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