Chapter 17
Integrating Crop and Landscape Management into New Crop Protection Strategies to Enhance Biological Control of Oilseed Rape Insect Pests

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Abstract The development of sustainable cropping systems is a major challenge for agronomists and crop scientists in many regions of the world. The prophylactic uses of broad spectrum insecticides are actually the main solution for farmers to control insect pests. Therefore, there is a growing need to develop innovative crop protection strategies through an integrated approach which aims at favouring natural enemies and enhancing biological control in agroecosystems. The development of such strategies requires a thorough understanding of agroecosystem functioning. In this chapter, we present the effects of different elements, from the field scale to the landscape scale that are known to enhance biological control in agroecosystems and limit pest damage with particular reference to oilseed rape. Linking integrated pest management and landscape ecology brings a regional perspective to the management of pest populations. Available techniques are often added together rather than combined in an integrated way and are rarely evaluated through environmental and economical criteria. Therefore, we present a methodological framework to design and assess sustainable cropping systems, with a particular emphasis on complementariness between models, systemic trials and more analytical approaches. Implementation of sustainable cropping systems implies the development of new integrated pest management strategies and thereby an increased participation of the different stakeholders from farmers to policy makers.

17.1 Introduction

Conventional modern agriculture was developed to increase and maximize productivity in order to meet increasing demands for food. The pursuit of this goal has led to an oversimplification of crop diversity at the field, cropping system and landscape levels, with increasing reliance on agrochemicals. Indeed, a range of farmers' practices have been developed without foreseeing any of the long-term consequences on the environment and on the ecological dynamics of agroecosystems. However, in

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today's socio-economic context, there is an increasing demand to reduce chemical inputs on arable crops and to develop more sustainable crop management strategies. Moreover, there is clear evidence that widespread resistance to pesticides resulting from the intensive use of broad spectrum insecticides necessitates the development of more sustainable and environmentally friendly insect pest management. Our aim in this chapter is to review the ways in which the cropping system, in its broadest definition, could be modified to enhance biological control in agroecosystems and limit pest damage. Consideration of different scales of analysis provides a good overview of how farmers' practices affect biological control and implications for integrated management of oilseed rape pests. Furthermore, multiple levels analysis permits to take into account the function of uncultivated areas on pest population dynamics and their biological control. In this scaling up approach we consider three different levels: the field level, the cropping system level and the landscape scale (from field edge management to spatial organization of crops and non-cultivated areas). These different levels include a crop management modification at the field scale, a diversification in crop sequences at the farm scale and spatial patterns at the landscape scale. At each level, we analyse which elements can enhance beneficial biological interactions and their impacts (direct or indirect) on pest regulation and pest damage with a particular emphasis on oilseed rape pests.

We will first present the effect of single practices at the field scale that play a role on crop attractiveness. Secondly, we will review the effect of crop management on the local habitat environment to promote biological control. Thirdly, we will summarize the work that has been carried out on the effect of crop diversification in space and over time at the field and the cropping system scale. Fourthly, we will discuss studies that have accounted for spatial pattern effect on pest population and pest regulation in agricultural landscapes. In conclusion, we will examine the perspective for designing new crop protection strategies and we will discuss the advantages of a complementary approach between modelling and on-farm diagnosis for integrated pest management.

17.2 Effect of Single Practices to Induce Pest Avoidance and Limit Pest Damage

There is a growing body of evidence that modifying some elements of crop management at the field scale can induce pest avoidance and limit pest damage. This strategy involves avoiding the simultaneous presence of crops and pests through different factors: the plant's ability to attract and repel pests (e.g., the 'push-pull' strategies), the plant's ability to recover from injury and the desynchronization between crop susceptibility periods, pest and predator life cycles.

17.2.1 Effect of Species, Cultivar and Crop Management on Crop Attractiveness for Pests at the Field Scale

We review here some important results concerning the effect of species, cultivar and crop management on crop location by oilseed rape pests. More information on the behavioural ecology associated with location of the oilseed rape crop by its

major pests and their key hymenopterous parasitoids is given by Williams and Cook (Chapter 7 this volume).

The capacity of insects to identify a host plant suitable for its feeding and reproduction depends on the morphological and/or metabolic characteristics of the plant. The pollen beetle (*Meligethes aeneus*), an oilseed rape pest, locates its host plant through visual and olfactory signals (Evans and Allen-Williams 1989, Evans and Allen-Williams 1998). The beetles are principally attracted by the yellow colour of the flowers and by certain chemical signals released by the plant. It has been shown that degradation products of glucosinolates attract insects specialised on cruciferous host plants (Feeny et al. 1970, Finch 1978, Free and Williams 1978). In particular, several studies have demonstrated the particular importance of alkenyl glucosinolates (which release low amounts of the volatile isothiocyanates (ITCs) most attractive to pests) for host plant location and selection (Smart and Blight 2000, Cook et al. 2006).

Based on the hypothesis that the production of glucosinolates by cultivars of winter oilseed rape (WOSR) and other Brassicaceae may attract pollen beetles, many studies have focused on the effects of host plants on insect orientation and feeding (Bartlet et al. 2004), oviposition behaviour (Borg and Ekbom 1996), and egg production of the pollen beetle (Hopkins and Ekbom 1999). Turnip rape (*Brassica rapa*) has been found to attract more pollen beetles in both laboratory and field conditions (Hokkanen 1989, Cook et al. 2002, 2006, Valantin-Morison and Quéré 2006, Rusch and Valantin-Morison 2010). The same effect has been reported for other oilseed rape pests such as cabbage stem flea beetle (*Psylliodes chrysocephala*) (Büchi 1995, Barari et al. 2005) and cabbage seedpod weevil (Carcamo et al. 2007).

Many physiological properties play a role in determining the attractiveness or repulsiveness of certain plant species, and stage of development seems to be a major factor in host selection. In particular, Cook et al. (2006) have demonstrated that pollen beetles preferred turnip rape to oilseed rape when both species had closed buds, preferred flowering plants regardless of the given species and had no preference for a particular species when both species were flowering. The importance of the stage of crop development in the implementation of a catch crop strategy has been confirmed by Valantin-Morison and Quéré (2006) and Rusch and Valantin-Morison (2010). The earlier flowering of turnip rape than of WOSR proved to act in synergy with the differences in glucosinolate synthesis between species discussed above.

Turnip rape is thus often used in this particular situation as a so-called trap crop. Simulations using a spatially explicit individual-based model show that for herbivores that actively immigrate from a nearby source via the field edge, a surrounding border trap crop is the optimal arrangement (Potting et al. 2005). Moreover, a trap crop can be used for the capture, in July and August, of the second generation of insect pests, to reduce population sizes just before hibernation (Husberg et al. 1985). In such a situation, landscape organization of these trap crops should be taken into account.

Nitrogen supply affects the glucosinolate content of cruciferous crops. As described above, these metabolites are involved in the plant host identification processes of pollen beetles and other oilseed rape pests. Indeed, several authors have shown that the rate of nitrogen application had a highly significant effect on

the glucosinolate content of the seeds (Milford and Evans 1991) or in the aerial parts of the plant (Markus et al. 1996). So nitrogen supply strategy (in terms of dates and rates) can play an indirect role on host plant attractiveness (Rusch and Valantin-Morison 2010). In the case of winter oilseed rape, Rusch and Valantin-Morison (2010) revealed an important effect of concordance between nitrogen supply and the number of stem weevil punctures. Indeed, plants which had received nitrogen earlier in the season (just before the first stem weevil flights) showed a greater stem elongation. As stem elongation is one of the most important criteria for stem weevil host selection, plants with greater elongation showed significantly higher numbers of punctures per main raceme and higher stem damage (Rusch and Valantin-Morison 2010).

Recent studies have shown that botanical extracts can function as insecticides, deterrents or repellents. Essential oils from plant species of the *Lamiaceae* have a broad spectrum of biological activity and lavender essential oil has been reported as interfering with orientation to, and selection of, host plants by a range of pest insects (Landolt et al. 1999, Mauchline et al. 2005, Cook et al. 2007). This lavender oil has been identified as a repellent and represents an interesting tool in push-pull pest control strategies developed against pollen beetle. Moreover, Cook et al. (2007) showed that parasitoids gave no significant responses to the odour of lavender oil in behavioural assays. This study suggests that lavender treated oilseed rape plants could be used as an element of an integrated pest management strategy as it would not reduce host habitat location by parasitoids of the given pest.

17.2.2 Effect of Species and Varietal Resistance on Pest Damage

Numerous studies have pointed out the important role of host plant resistance in arthropod pest management (Van Emden 1991, Kogan 1994, Gatehouse 2002, Sharma and Ortiz 2002). Kogan (1994) explained that the damage caused by an insect pest to a crop depends on the feeding habit of the pest species, the size of its population, and the capacity of the plant to withstand the type and amount of injury that results. One of the most important biotic factors that regulates pest population size is the adequacy of a plant as a host for the insect pest. Therefore, Kogan (1994) highlighted that resistance of a host plant to an insect pest is expressed through properties that enable the plant to restrain the growth of the pest population (antibiosis phenomenon) or the capacity of the plant to withstand attacks and recover from injury. In cruciferous plants, all three types of insect resistance modalities (antixenosis, antibiosis and tolerance) have been found in the case of various insect pests (Palaniswamy 1996). For example, Dosdall et al. (1994) compared the susceptibilities of species and cultivars of oilseed rape and mustard to infestation by root maggots (*Delia* spp.) and found that oilseed rape was the most susceptible. The authors found that differences in susceptibility occurred among and within oilseed rape and Indian mustard species, but generally the differences were greater between species than between cultivars within species. This study demonstrated that the mechanism of resistance by cruciferous species under study to infestation

by *Delia* spp. is antixenosis. Moreover, Ellis and Farrell (1995) have compared the response of six *Brassica* accessions to aphid infestations and found both antixenotic and antibiotic resistance to cabbage, while Palaniswamy (1996) reported that both antixenosis and tolerance mechanisms were found in the resistance of cruciferous plants (e.g., *Sinapsis alba*, *Brassica juncea* and *Brassica napus*) to the flea beetle (*Phyllotreta striolata*). Lamb et al. (1993) identified a line derived from *Brassica rapa* that shows quantitative resistance to flea beetles (*P. striolata*). This resistance is attributed to a low level of antixenosis, rapid growth at the cotyledon stage, and tolerance to damage. The existence of natural variation in response to pest infestations among oilseed rape cultivars and *Brassica* species suggests the potential for breeding resistant *B. napus* cultivars. Further investigations are necessary in order to understand the underlying mechanisms and to develop more adapted cultivars.

17.2.3 Effect of Nitrogen Supply and Cultivar on Crop Condition and Crop Ability to Reduce Pest Damage

Numerous studies have pointed out that the oilseed rape crop can compensate for damage caused by different herbivores (Williams and Free 1979, Lerin 1988). Williams and Free (1979) showed that the removal of up to 60% of the buds caused no yield loss. Compensation mechanisms take place at different levels of the plant and through different yield components as a function of pedoclimatic conditions, timing of herbivore attacks and crop status. For example, pollen beetle attacks involve loss of apical dominance and result in a stunting of the attacked racemes and the outgrowth of side racemes (Nilsson 1994) with more pods per side raceme (Podlaska et al. 1996). Pollen beetle attacks reduce in most cases the number of seeds per pod due to the delay in pod formation. Thus compensation for seed loss takes place through an increase in seed weight. It is also known that oilseed rape crops can compensate for changes in plant density. Indeed single plants in low density populations grow larger and produce more pods and more seeds than those in high seeded density. As the ability of the crop to compensate for pest damage directly depends on crop status, nutritional resources and nitrogen availability, plants with sufficient available nitrogen in their direct environment will be more able to reduce yield losses due to herbivory. Indeed, Valantin-Morison et al. (2007) found a negative correlation between nitrogen availability in the soil and pollen beetle damage certainly due to nitrogen effect on plant vigour and compensation ability. The synchronization between pest attack and nitrogen supply appears to be very important to consider even if little is known about it.

Insects choose the most favourable host plant for the development of their eggs, as a function of their potential capacity to meet the needs of the larvae. Several studies have shown that pollen beetles adjust the number of eggs laid per bud and the amount of resources in the egg for larval development as a function of plant quality (Hopkins and Ekbom 1996, 1999). In addition, Nilsson (1994) showed that females selected flower buds as a function of size, showing a marked preference for buds between 2 and 3 mm long and refusing the suboptimal buds unless there

was very strong competition for oviposition. Another pest of oilseed rape crops, the cabbage root fly has also been shown to select the most favourable plants for oviposition on the basis of stem diameter (Dosdall et al. 1996, Valantin-Morison et al. 2007). Finally, the architecture and height of the plant also seem to play an important role in host selection mechanisms (Kostal 1993, Rojas and Wyatt 1999, Finch and Collier 2003). The amount and timing of nitrogen supply may play a significant role in determining the potential attractiveness of the crop to pests by modifying plant quality and architecture. Indeed, high nitrogen amounts could induce the production of large flower buds which is more favourable for pollen beetle oviposition but also produce more secondary racemes, which allow better compensation for pest damage.

Even if some knowledge has been acquired, the general understanding of the effect of some crop practices, particularly nitrogen supply and cultivar, on crop response to pest infestations in oilseed rape, is not well established. Nevertheless, this understanding is the cornerstone of establishing injury and economic thresholds for oilseed rape pests which are still lacking in general or showing great variability between countries (as demonstrated by Nilsson 1994, see also Williams Chapter 1 this volume).

17.2.4 Effect of Sowing and Harvesting Dates on the Synchronization Between Crop, Pest, and Predator Life Cycles

One of the strategies underlying pest avoidance is the desynchronization between crop susceptibility periods and the biological cycle of pests. This effect is widely known in cereal and oilseed crops. Dosdall and Stevenson (2005) demonstrated that the sowing date of oilseed rape strongly affects flea beetle (*Phyllotreta cruciferae*) damage. Indeed, the damage was greater on spring-seeded oilseed rape than on plants seeded in the autumn. Flea beetle feeding damage to oilseed rape apical meristems can prevent a compensatory response, but by the time of greatest injury, winter oilseed rape had well-developed, enlarged apical meristems making them less susceptible to damage. Winter oilseed rape enabled plants to progress beyond the vulnerable cotyledon stage by the time that most flea beetle damage was inflicted, resulting in less crop damage.

The same effect was observed on the maize crop. Early-sown maize is less susceptible to maize earworm and stem borer, *Diatrae grandiosella* (Bajwa and Kogan 2004). This lower susceptibility results from the fact that *D. grandiosella* tends to lay fewer eggs on more mature plants, which have already passed their critical growth stage before most of the larvae begin to feed (Herzog and Funderburk 1985). Pest avoidance can also be achieved by modifying harvest date to limit the damage caused by various pests attacking the crop shortly before harvest (Flint and Gouveia 2001). For instance, for *D. grandiosella* on maize, in addition to the effects of early sowing described above, early sown maize can be harvested before fully grown pre-diapause larvae have girdled the plants and caused yield losses through

lodging (Bajwa and Kogan 2004). But sowing date effects can be antagonistic when considering different pest populations. Indeed, Valantin-Morison et al. (2007) have shown that sowing oilseed rape early tended to increase cabbage root fly damage, whereas it was associated with a lower level of attack by cabbage stem flea beetle.

Effects of sowing date on the incidence of the barley yellow dwarf luteovirus have been reported (McKirdy and Jones 1997). The virus is transmitted by aphids and the main vectors are bird cherry-oat aphid (*Rhopalosiphum padi*) and grain aphid (*Sitobion avenae*). As the major flight of aphids peaks in September and October, delayed sowing reduced the number of aphids per plant and decreased disease incidence. Effects of sowing date on the severity of other crop diseases have also been reported (e.g., Krupinsky et al. 2002). In the case of oilseed rape, Aubertot et al. (2004) demonstrated that early sowing dates reduced damage caused by *Leptosphaeria maculans*, the causal agent of phoma stem canker, one of the most important oilseed rape diseases. In this pathosystem, damage at harvest is most severe if infection occurs soon after emergence (Brunin and Lacoste 1970). As the primary inoculum of *L. maculans* generally peaks between September and December (West et al. 2002), early crop sowing leads to a lower risk of infection just after emergence than other sowing dates.

Moreover, harvesting can have a major impact on field fauna. In fact, it produces a brutal perturbation of the agroecosystem involving microclimate changes that impact natural enemies at the field scale. According to Riechert and Lockley (1984) harvest effects have a greater impact on spider communities than does the use of pesticides. Harvest effects depend on the time at which harvest actually occurs. For spring crops (such as maize) harvest is sufficiently late for most of the predatory species to be at the end of their activity period and to have reached their overwintering sites. For winter crops (such as winter oilseed rape and most of the cereals) harvest dates generally coincide with the maximum abundance and activity of some predators (Büchs 2003). This demonstrates that sowing and harvest date can have an important effect on predator population and pest regulation. But possible antagonistic effects, highlighted above, imply that pest avoidance should not be seen as a simple technical operation that is easy and straightforward to apply. Instead, many interactions must be taken into account when designing pest management strategies. Overall, pest avoidance strategies should be designed within the conceptual framework of integrated crop management (as defined by Royer et al. 1999).

17.3 Crop Management Effect on Local Habitat Environment to Promote Biological Control of Insect Pests

Different aspects of crop management affect the local condition of the field and influence (directly or indirectly) pest dynamics, pest damage and natural enemies. We review the most important factors of crop management with particular reference

to oilseed rape. The objective of this part is to present the main local elements that could be combined in an integrated pest management approach.

17.3.1 Direct Effects of Soil Tillage on Predator and Parasitoid Populations

Parasitoid populations are very susceptible to post-harvest soil tillage as the majority of the parasitoid species of oilseed rape pests overwinter in the soil of rape fields. Thus, it has been shown that soil cultivation techniques used to establish the crop following rape can greatly influence survival, emergence rates and then parasitization of oilseed rape pests of the following year (Nilsson 1985, 1994, Hokkanen et al. 1988). For further details on the effects of soil tillage on parasitoids of oilseed rape pests, see Nilsson (Chapter 11 this volume). Reduction in arthropod densities caused by different crop management activities (which cause direct mortality) varies from 25 to 60% according to the different taxa (Thorbek and Bilde 2004), and spiders seem to be more vulnerable to mechanical crop treatments than carabid and staphylinid beetles. Moreover, important and sometimes higher effects of habitat disruption are observed a few days after the crop management operation (Thorbek and Bilde 2004).

The timing of tillage procedures also has an important impact on predator populations. Ploughing in spring has a more harmful effect on ground beetle populations than autumn ploughing. It is known that tillage in late summer or in autumn is more beneficial to population development of some beetles than spring ploughing. It is assumed that later in the season most of the predators will have moved out to their overwintering sites, mostly in uncultivated areas, or will have moved deeper into the soil (Büchs et al. 1999).

17.3.2 Effects of Mulch on Generalist Predators and Biological Control

Physical disturbance of the soil caused by tillage and residue management is a crucial factor in determining soil biotic activity and species diversity in agroecosystems (Altieri 1999). Soil tillage affects organic matter characteristics and location, water regime and structure of the soil surface (Holland 2004). Reduced tillage (with surface placement of residues) creates a relatively more stable environment, encourages the development of more diverse species (in particular decomposer communities) and slower nutrient turnover. Several studies on different crops including oilseed rape have shown that increasing the structural complexity of the soil through the addition of organic matter almost always leads to an increase in the diversity of generalist predators (ground beetles, spiders and hoverflies) (Kromp 1999, Schmidt et al. 2004, Pullaro et al. 2006, Brevault et al. 2007). In most cases it leads to a decrease in the populations of certain crop pests (Zehnder and Hough-Goldstein 1989, Brust 1994, Schmidt et al. 2004, Pullaro et al. 2006, Zehnder et al. 2007).

Landis et al. (2000), in their review of habitat management to conserve natural enemies of arthropod pests, reported that manure and straw increased numbers of the carabid *Bembidion lampros*, an egg predator of the cabbage root fly, and increased total carabid populations in cabbage. This increase was apparent even into the year following the last application and was attributed to increased reproduction by the predators, which, in turn, may have resulted from the observed increase in alternative prey availability. Indeed, the presence of decomposing organic matter at the surface of the soil provides predators with alternative prey when crop pests are no longer present in the plot. Therefore, no-tillage systems, such as direct drilling, that leave crop residues on the soil surface, increase the populations and impacts of predatory carabids. Kendall et al. (1991) even showed that, in winter barley crops, the amount of straw present on the soil surface was positively correlated with the diversity of polyphagous predators and negatively correlated with barley yellow dwarf virus infection levels. Some studies have also reported that mulch causes disturbances in pest prospecting and approach behaviour. Indeed, pests are less efficient at host plant location, due to physical barriers and release of allelochemical substances from the decomposing (Mabbett 1991) or living mulch (Finch and Collier 2000). Büchs and Katzur (2004) confirmed that reduced-tillage favours natural enemies in the case of organic oilseed rape. In their study, they focused on the occurrence and control of rape pests by comparing three different treatments: a plough/comb harrowing treatment, a mulch/comb harrowing treatment and a mulch/hoeing treatment. They found that the mulch/comb harrowing treatment promoted the natural enemies of oilseed rape pests compared to the other treatments. However, higher risk of yield loss due to weed populations was found in the case of the mulch/comb harrowing treatment. The mulch/hoeing treatment appeared to reduce the weed population and yield loss risks but also reduced natural enemies and increased pest damage. Thus no consensus has been reached about the effects of mulch left by simplified soil cultivation, and indeed, in some cases, the number of pests increased. Mabbett (1991) has reported an enhancement of slug (*Deroceras reticulatum*) populations after mulch application to winter barley fields. Different hypotheses have been proposed to explain the enhancement effects of mulch on pest populations. First of all, a lack of natural enemies, including large ground beetles specialising in mollusc predation, due to deleterious insecticide treatments may be responsible for such effects (Chabert and Gandrey 2005). Secondly, deficiencies in the ecological infrastructure (Bohan et al. 2000, de la Peña et al. 2003, Holland et al. 2005), with slugs being favoured by the presence of organic matter can also be responsible for this enhancement. Finally, an overabundance of alternative prey, such as springtails, aphids, fly eggs and larvae, may favour pest populations (Mair and Port 2002, Symondson et al. 2006).

For many crops, the effects of mulch on pest activity and generalist predators appear to be well known but little is known about its effects on oilseed rape-specific pests. Furthermore, as mentioned in part 1 of this chapter, leaving mulch on the soil surface should not be thought of as the sole alternative to pesticide use, since many interactions between other practices and other pests must be taken into account.

17.3.3 Effect of Pesticide Use on Natural Enemy Populations

The impact of insecticides on parasitoid populations has been addressed by Ulber and Klukowski (Chapter 13 this volume). Many parasitoid species of different oilseed rape pests emerge 1–2 weeks before rape flowering and are particularly active in the crop during the flowering stage, searching for suitable hosts. Thus, they can be very affected by late insecticide spraying occurring around flowering (Nilsson 1994, Nitzsche and Ulber 1998, see also Johnen et al. Chapter 15 this volume).

Other effects of pesticides on natural enemies have also been reported on different crops including oilseed rape. In the literature, pesticides are considered to be one of the main causes for biodiversity loss (Ewald and Aebischer 2000). Indeed, numerous studies have illustrated the impact of pesticides on different communities of natural enemies (Chabert and Gandrey 2005, Koss et al. 2005, Tietjen and Cady 2007). Some have pointed out that the side effect of insecticide use on natural enemies can be the origin of important pest proliferations (Gordon and McEwen 1984). Even if it is admitted that species inhabiting higher parts of the field vegetation are more exposed to pesticide effects (Vickerman 1992), it has been shown that pesticide use decreased the number of arthropod species (hypogeous or epigeous species) at the field scale and decreased biological control by natural enemies (Burn 1988, Duffield 1991). Stark et al. (2004) have shown that life story attributes as well as population structure at the time of pesticide exposure both play a major role in population susceptibility to pesticides. Therefore, the authors have highlighted the need to explicitly consider differences in life history variables among species when calculating compatibility of pesticides and biological control agents as well as the population structure of beneficial species at the time of pesticide application. Furthermore, herbicides and fungicides have important indirect effects on arthropod communities (such as phytophagous or flower-visiting arthropods) as they generally suppress their resources (Landis et al. 2000). Büchs et al. (1991) also showed that insecticide seed treatments on oilseed rape may have seriously affected epigaeic predators such as ground beetles, because even predatory species are partly phytophagous.

17.4 Effect of Crop Diversification in Space and Over Time on Biological Control: Crop Succession and Within-Crop Diversification

Diversified cropping systems in space and over time, such as those based on intercropping, agroforestry, cover cropping and on more diversified crop rotations have been the target of much recent research. This interest is partly based on the emerging evidence that these systems are more stable and more resource conserving (Vandermeer 1995). Indeed, crop monocultures are environments in which it is difficult to induce efficient biological pest control because these systems lack

adequate resources for effective performance of natural enemies. Therefore such systems are more susceptible to pest or disease outbreaks. Some elements at the field and farm scales can be used to increase crop diversity and induced biological control.

17.4.1 Diversifying Species in Crop Succession: Effect on Pests and Natural Enemy Communities

Rotation of annual crops has been empirically developed by farmers to reduce and control soil-borne pest and disease proliferation. In the middle of the last century, a well developed rotation consisted of six to eight different crops in sequence (Häni et al. 1998). An increase in economic pressure and food demand pushed farmers to spread more pesticides and to maximise land use. The rotation was reduced to a few species, leading to an increase in pest proliferation and a decrease in biodiversity of beneficial species.

A meta-analysis (Tonhasca and Bryne 1994) showed that crop diversification led, in 52–70% of cases (21 studies), to a decrease in pest density. Since this study, several publications have taken part in the debate over the consequences of crop diversification for pests (Coll and Bottrell 1995, Theunissen et al. 1995, Khan et al. 1997, Schellhorn and Sork 1997, Harmon et al. 2003, Hooks and Johnson 2003, Aquilino et al. 2005, Costamagna and Landis 2006, Khan et al. 2006, Björzrkman et al. 2007). Eight of these publications have reported that crop diversification successfully decreased the populations of all or some pests and two studies found that crop diversification had no effect on pest populations.

Other studies showed that diversifying crop succession increased some natural enemies. Indeed, Büchs et al. (1997) studied the effects of different crop rotation intensities on the arthropod community in a sugar beet rotation and an oilseed rape rotation. They showed that certain pest species were enhanced by an increasing intensity of crop rotation, while some beneficial insects were not able to build up stable populations in arable crops in such intensive succession. The authors found that the number of individuals, species richness, body length, and reproductive rates of beneficial insects increased with progressive extensification of crop sequences and especially in set-aside areas with natural succession.

However, higher crop diversification within crop sequence does not always increase abundance or activity of pest antagonists. Indeed, different studies have compared carabid populations between different crop successions including monoculture and no significant differences were found (Holland et al. 1996, Winstone et al. 1996, Kromp 1999).

Some advantages of crop diversification are also illustrated by the use of break crops to control soil-borne diseases. The term 'break crop' refers to breaking the life cycle of a crop-specific pathogen by growing a non-host crop in the rotation. Winter oilseed rape and other cruciferous plants could be considered as a biofumigation crop (Kirkegaard et al. 2008).

17.4.2 Increasing Within-Field Diversity: Effect of Cover Cropping and Intercropping on Pests and Natural Enemy Communities

Cover cropping and intercropping increase the diversity within the field. Plant cover has many roles like improving the resources and growth conditions or decreasing the impact of pests, thereby increasing crop productivity. Cover crops can be separated in two main categories: annuals grown during an off-season that are killed before planting a cash crop, providing a mulch; and living mulches that grow at the same time as the cash crop for all or part of the growing season, resulting in an intercropping system.

An increasing body of literature demonstrates that pest proliferation decreases when crop specific diversity increases (Landis et al. 2000, Ferron and Deguine 2005). Many studies have shown that the introduction of a cover crop in perennial and annual crops may improve pest control (Wyss 1995, Pickett and Bugg 1998, Altieri and Nicholls 2004, Pfiffner and Wyss 2004, Broad et al. 2008). In fact, perennial crop systems are potentially more amenable to conservation biological control than are ephemeral annual systems because they are subject to lower levels of disturbance. Thus, resident populations of natural enemies may persist from year to year in perennial crops (Landis et al. 2000). However, cover crops may also aggravate pest damage or favour certain new pests when the plants used provide the pests with a key resource (Pfiffner and Wyss 2004). In 16 published cases reviewed by Russell (1989), natural enemies were more abundant in polycultures than in monocultures in 10 cases, in four cases no effect was reported, and in two cases predator numbers were lowered. Moreover, in a review, Andow (1991a) analysed the results of 209 studies on relations between intercropping and pest populations (287 pest species). Pests were significantly reduced in 52% of the cases compared to monocultures and were more important in 15%. These conclusions have been corroborated by different studies (Nickel 1973, Perrin 1977, Risch 1983) and are explained by different mechanisms.

First of all, the introduction of a cover crop produces indirect effects on pest populations involving host quality (Trenbath 1993) but also plant/crop architecture and crop microclimate (Altieri and Liebman 1986, Francis and Clegg 1990, Landis et al. 2000). Indeed, intercropping often leads to important changes in crop architecture and many authors have shown that insect pest behaviour (such as feeding, flight or reproduction) are very susceptible to general crop architecture. Cabbage moth (*Mamestra brassicae*) is affected by plant height (Rojas and Wyatt 1999) while the main factor governing the selection, during the landing, of the site most suitable for cabbage root fly was the conspicuousness of the plant (Kostal 1993).

Root (1973) incorporated the possible mechanisms that underlie the response of herbivore pest to habitat diversification into two hypotheses: the enemy hypothesis (first formulated by Pimentel (1961)) and the resource concentration hypothesis. The first one exposed indirect effects of the intercropping system on pests and states that the observed reduction of herbivores on intercropped systems is partly due to the attractiveness of the intercrop for more abundant and/or efficient predators and

parasitoids, presumably because of the greater availability of resources and habitats as compared to the monoculture.

Intercropping also has more direct effects on the pest. The resource concentration hypothesis formulated by Root (1973) states that 'herbivores are more likely to find and remain on hosts that are growing in dense or nearly pure stands; the most specialized species frequently attain higher relative densities in simple environments; and, as a result, biomass tends to become concentrated in a few species, causing a decrease in the diversity of herbivores in pure stands'. According to this hypothesis the probability of pests finding their host plant, remaining on it and reproducing on it, is higher in monocultures than in a mixture of several species because the resource is diluted among other resources (Tahvanainen and Root 1972, Root 1973). This hypothesis therefore predicts a negative relationship between plant diversity and the level of invertebrate phytophagy (Root 1973), regardless of any interaction with the natural enemies of pest species. As emphasised in many studies exploring this hypothesis, the observed effects could have resulted from different mechanisms such as arthropod movement in approaching the crop and within it, immigration and emigration, and host finding and acceptance (Risch 1983). Other mechanisms such as barrier effects, as well as visual and olfactory effects on host location have also been reported (Perrin 1977, Altieri and Liebman 1986). Different studies (Risch 1983, Andow 1991a, b) have suggested that mechanisms of resource concentration rather than natural enemies contribute to lower herbivores numbers in polycultures.

Little is known about the specific effects of increasing within-crop diversity in the case of oilseed rape. Weiss et al. (1994) studied the influence of an intercropped agroecosystem of oilseed rape, canola-type (*Brassica napus*) and field pea (*Pisum sativum*) on the population level of the flea beetle (*Phyllotreta cruciferae)*, but no effect in reducing chrysomelid loads, nor increasing yield were recorded for the intercropped system. Butts et al. (2003) in their study on the effect of intercropping oilseed rape or pea with barley on assemblages of ground beetles (Coleoptera: Carabidae), found no effect of the intercropping system. Finally, Hokkanen (2008) reported that intercropping experiments revealed no differences in the number of pollen beetles per plant, percentage of parasitism, or overall predator activity densities between the monocrop and intercrop. However, the number of emerging new generation pollen beetles appeared drastically reduced in the intercrop as compared with the monocrop, which produced about five times as many F1 pollen beetles as the intercrop per surface area, or about two and half times as many per rapeseed plant. The author concluded that higher predator pressure (lower total number of prey, but equal number of predators) in the intercrop may be an explanation for such effects.

17.5 Influence of Spatial Context on Oilseed Rape Pests and Their Biological Control in Agricultural Landscapes

Modern agricultural landscapes generally consist of a changing mosaic of cultivated and uncultivated habitats. Agricultural intensification has led to a marked simplification and fragmentation of rural landscapes that are nowadays usually characterized

by a high proportion of arable fields, an enlargement of field sizes and a high degree of fragmentation of small natural habitats. There is a growing body of evidence showing that species community structure and abundance and more generally biotic interactions have to be considered at a spatial scale much wider than a single patch of habitat. It is therefore important to link the biological characteristics and ecological processes of the given organism to spatial pattern. Indeed, spatial context does not influence all species in the same way and responses to landscape structure are species specific (i.e., species ability to disperse, species life cycle) (Dunning et al. 1992, Fahrig and Merriam 1994).

17.5.1 Effect of Semi-Natural Areas on Pests and Natural Enemy Populations

Even in situations of considerable crop diversity, all fields constitute ephemeral habitats which could be considered a hostile environment for many animal species, including natural enemies of phytophagous insects (Bianchi et al. 2006). On the contrary, non-cultivated habitats in rural landscapes, such as hedgerows, field margins, fallow land and woods, are relatively undisturbed, largely unchanging areas and provide both woody and herbaceous habitats. Non-crop habitats provide life support functions, maintaining the presence of alternative hosts and prey for predator and parasitoid populations (Sotherton 1984, Pickett et al. 2000, Denys and Tscharntke 2002). They can also provide sources of pollen and nectar, which are essential for many insects (Pickett and Bugg 1998). Finally, woody habitats often provide a more moderate microclimate than field centres, protecting parasitoids against extreme temperature variations (Rahim et al. 1991) and provide good habitats for overwintering of natural enemies and pests. According to Keller and Häni (2000), nine out of 10 auxiliary species need non-crop environments at some point in their life cycle, whereas this is the case for only one of two pest species. Therefore, most auxiliary species are heavily dependent on the resources provided by semi-natural environments requiring them to travel back and forth between uncultivated habitats and the given crop.

17.5.2 Effect of Landscape Context on Pests, Natural Enemies and Diseases

According to Pulliam (1988) and Pulliam and Danielson (1991) landscape mosaic can be conceived as functioning in terms of different sources and sinks for parasitoid populations. Non-crop habitats serve as the starting point for field colonization to various extents for many species beneficial, damaging or neutral to crops (Nentwig 1988, Dennis and Fry 1992, Thomas et al. 1992, Denys and Tscharntke 2002, Marshall 2004) and thus distance and spatial arrangement between fields and non-crop areas are important. It has been suggested that parasitoids and predators may generally act at smaller spatial scales than phytophagous pests (Roland and Taylor 1997, Zabel and Tscharntke 1998). This may account for the frequent observation

that the intensity of the ecological pest control services, mediated by predators and parasitoids, decreases with increasing distance to the non-crop refuge zones (Altieri and Schmidt 1986, Klinger 1987, Collins et al. 2002). Thus, the spatial and temporal dynamics of many auxiliary species populations depend heavily on the characteristics of the landscape (Marino and Landis 1996, Elliot et al. 1998, Thies and Tscharntke 1999, Östman et al. 2001, Kruess 2003, Sarthou et al. 2005, Roschewitz et al. 2005), particularly in conventional production systems in which the presence of auxiliary species in crops is becoming increasingly dependent on the regular arrival of individuals from semi-natural habitats to re-colonize the field (Schmidt et al. 2005). The importance of local abundance of source habitats, refuges, and alternative hosts in the landscape on crop disease prevalence has also been demonstrated (Plantegenest et al. 2007). Landscape structure appeared to have an important effect on disease dynamics as pathogens disperse through different spatial dependent mechanisms, such as aerial dispersal to vector-borne viruses. Therefore some elements in the agricultural landscape, that influence air motion for example, may act as barriers limiting disease spread, or inversely as corridors facilitating the dispersal of the pathogen.

A literature review by Bianchi et al. (2006) analysed 28 studies focusing on pest pressure and/or on natural enemy populations in relation to landscape composition in the case of various crops. The authors found that pest pressure was reduced in complex landscapes in 45% of 10 studies reviewed. They also found that natural enemy activity was enhanced by complex landscape in 74% of the studies reviewed (24 publications). In 21% of the studies reviewed, no effect of landscape composition was reported, while in 5%, natural enemy activity was lower in complex than in simple landscapes. Even if the majority of the studies showed higher natural enemy activity, only 45% of them appeared to reduce pest pressure in more complex landscapes indicating important variability in organism responses to landscape structure.

For instance, in the case of oilseed rape pests, relations between pollen beetle, pod midge, stem weevil and landscape composition have been reported from two main studies (Thies et al. 2003, Zaller et al. 2008b). In these, pollen beetle responses to landscape complexity are contrasted. Thies et al. (2003) found that pollen beetle activity appeared to be negatively correlated to landscape complexity and that parasitism rates were positively correlated to landscape complexity. However, Zaller et al. (2008b) showed that the abundance of pollen beetles were negatively related to oilseed rape area and positively related to woody areas. Here the results suggest that complex landscapes enhanced pest populations either by supporting a greater variety of alternative host plants or by providing more suitable habitats for overwintering. This difference of response to landscape characteristics probably comes from the different landscape metrics chosen for quantifying landscape patterns, the landscapes and regions per se used in these studies, and also from fundamentally different methodological approaches. Effects of spatial context at the landscape scale on oilseed rape pests and their biological control are reviewed in more detail by Frank et al. (Chapter 10 this volume), and by Thies and Tscharntke (Chapter 9 this volume).

17.5.3 Effect of Field Margins on Pest Regulation

Vegetative buffers in agricultural landscapes can provide a range of important eco-
logical services, including conservation of native flora and fauna, enhancement of
biological pest control, and reduction of agrochemical drift. The characteristics of
field margins, such as age and composition, contribute to the efficiency of these
buffer zones on pest regulation.

First of all, it has been reported that the effects of these strips on the biodiversity
of auxiliary species heavily depend on the plant species within the margin. Indeed, it
is known that the provision of adequate floral resources favours the development and
activity of predator and parasitoid populations (Rebek et al. 2006). Different studies
have been interested in determining the species composition of flower strips most
favourable to all sorts of auxiliary species important for crops (Nentwig et al. 1998,
Chiverton 1999, Wäckers 2004). Moreover, many studies have been carried out on
the effects on flower-dependent specialist predators and parasitoids of either single
species flowering strips (Lővei et al. 1992, Hickman and Wratten 1996, Petanidou
2003, Pontin et al. 2006) or on flowering strips composed of several species (Klinger
1987, Sutherland et al. 2001, Rebek et al. 2006, Pontin et al. 2006). Cultivating a
well-studied single flower species ensures the conservation of a particular target
beneficial species and minimises the risk of non-target effects, such as inadver-
tently promoting populations of pests (Baggen et al. 1999), higher-order predators
or hyperparasitoids (Stephens et al. 1998). In contrast, the use of flower mixtures
diversifies the resources available, which caters for a greater diversity of pollinators
and natural enemies because of selective feeding on the various different floral com-
ponents. For the moment, no specific study has been reported on the effects of floral
composition of field margins on biological control of oilseed rape pests.

Many studies have also shown that these flowering strips, favouring the devel-
opment of flower-dependent specialist predators and parasitoids, also make very
good refuges, after 2–3 years of ecological maturation, with the planting of sev-
eral tussock grasses for ground-dwelling auxiliary species (Nentwig 1988, Frank
and Nentwig 1995, Pfiffner and Luka 2000, Meek et al. 2002). Field margins, with
a naturally diverse flora or with sown 'wild flowers', harbour the greatest abun-
dance and diversity of arthropods (Lagerlöf and Wallin 1993). Thomas et al. (2002)
also observed that the incorporation of wildflower seed into tussock grass mixtures
sown for beetle banks provided resources for bumblebees, parasitoids, hoverflies
and butterflies.

Secondly, many different studies have shown that the age of field margins plays
an important role in biological control. Frank (1996) showed significant effects of
sown weed strips of different age on the diversity of epigaeic predators (ground bee-
tles and spiders) as well as of hover flies (Syrphidae) and solitary wasps (Sphecidae)
and their tendency to disperse into adjacent crops. Büchi (2002) showed that par-
asitism rates of pollen beetle larvae by *Tersilochus heterocerus* were significantly
higher in fields with wild flower strips than in fields with adjacent extensively-
managed meadow. He also showed that, in both cases, pollen beetle larval density
within the crop increased with increasing distance from field borders. Thies and

Tscharntke (1999) showed that age of field margin strips and fallow habitats had an important effect on parasitism rates of pollen beetle larvae. Old fallow field margins or fallow habitats exhibit higher pollen beetle mortality. These types of old habitats are less disrupted areas than cultivated ones and allow parasitoid populations to build up and to disperse into the crop. However, some studies have also shown that field margins did not always increase natural enemies and biological regulation of insect pests (Holland et al. 2008). Pfiffner et al. (2009) in their study of the impact of wildflower strips on biological control of cabbage Lepidoptera (*M. brassicae*, *Pieris rapae*) demonstrated that the provision of wildflower strips does not necessarily enhance biological control and suggested that site-specific environmental factors strongly affect their impact.

These results indicate that field margins are not systematically beneficial for pest control, since it depends on floral composition as well as on the age of the boundary and local conditions. Moreover, when designing low input cropping systems, it is necessary to consider field margin management in order to adapt cultural practices to the ecological services provide by the boundary.

17.5.4 Relevance and Robustness of Landscape Scale Approaches for Effective Biological Control

All the studies which have been carried out at the landscape scale provide evidence that the conservation of arthropods and the enhancement of biological control need a spatial context perspective. Furthermore, they allow us to understand how pest control could be strengthened by giving a basis for predicting how pest species and their natural enemies respond to landscape context. However, the effect of landscape characteristics in the biocontrol of pests remains a matter of debate. Firstly, the enhancement of natural enemy populations does not necessarily imply an effective pest control and the relationships between crop and non-crop habitats are complex and sometimes antagonistic (Thies and Tscharntke 1999, Valantin-Morison et al. 2007, Zaller et al. 2008a). Secondly, the effects of higher biological control on productivity are not well known and landscape effects on pest populations and crop damage have rarely been documented even though they are much more relevant than any effect on natural enemies (Bianchi et al. 2006). Many studies at the landscape scale suffer from the lack of information about the real effects of crop management and higher biodiversity on crop damage and yield losses. Indeed, Bianchi et al. (2006), in their review, found 10 studies dealing with pest densities and demonstrated that lowered pest pressure in complex landscape was found in 45% of the studies. In instances where agricultural biodiversity has enhanced biological control and reduced pest densities, the need for pesticide inputs may be lessened although linking higher biodiversity to higher yields through pest regulation is very difficult to demonstrate (Gurr and Wratten 2000). Thus, although the highly diverse auxiliary species communities present at the edge of the plot are capable of providing the crop with a certain level of protection (Klinger 1987, Hausammann 1996, Platt et al. 1999) without generally acting as a source of crop pests (Lagerlof and Wallin 1993,

Geiger et al. 2005), agronomists still have to demonstrate the beneficial effects on production and identify the key points relating to the cultivated field, neighbouring plots, and the surrounding area that might accentuate these effects.

In most of the studies previously cited, soil occupation within the landscape (in terms of crop or non-crop area, for example) was the only factor taken into account. Cropping systems in the farming landscape have generally been neglected (e.g., distribution of resistant varieties, ploughed and unploughed area, or frequency and timing of pesticide utilisation). A spatial consideration of the different cropping systems allocated throughout the landscape will allow a better comprehension of interactions occurring at a scale larger than the crop field. Agronomists designing crop protection strategies that maximise biological control at the landscape scale should integrate already existing ecological principles in order to build practical alternative systems that suit the specific needs of farmers and society. Because of the emerging importance of interactions between the field crop and the surrounding environment and the relative importance of spatial organization, agronomists have to reconsider the scale at which pest management strategies are being designed and have to use a less physicochemical approach to the environment than in the past.

17.6 Designing New Crop Protection Strategies: How Can We Use Crop Management and Landscape Effects to Improve Pest Management?

Integrated pest management strategies focus on long-term management of pest populations through a combination of techniques, including enhancing biological control, use of resistant varieties, chemical control, adoption of cultural practices such as crop rotation or sowing date to make habitat less convenient to pest population development, or physical control methods such as mechanical, pneumatic, thermal, or electromagnetic techniques for reducing pest populations. Pesticides are used only when careful monitoring indicates they are needed according to pre-established guidelines based on treatment and economic thresholds. More generally, these methods are the cornerstone of Integrated Crop Management strategies which are considered as a reasonable trade-off between profitability and environmental protection avoiding waste, enhancing energy efficiency and minimizing pollution (El Titi et al. 1993, see also Nilsson Chapter 16 this volume). The combinations of different techniques to achieve integrated pest management with more biological control involve profound modifications in the nature of the cropping system and different considerations. Firstly, the scale issue requires linking integrated pest management strategy to more ecological knowledge, especially landscape ecology. Secondly, designing innovative cropping systems needs a systemic approach that considers the entire agroecosystem and that particularly pays attention to farming techniques as well as economical and environmental impacts.

17.6.1 Linking Integrated Pest Management Against Insect Pests and Landscape Ecology

Designing integrated crop management strategies for farmers aims to achieve different objectives: (i) a production purpose (crop performance and quality of products), (ii) socio-economic imperatives (farm organization, farm income) and (iii) environmental issues (limitation of pesticides and nitrogen discharged into the environment, minimization of water and energy use). The integrated pest management paradigm holds that pests and their management exist at the cross roads of three multidimensional major fields of study: ecology, socio-economy and agriculture in hierarchical order, with ascending levels of complexity and expanding spatial scales. Based on these considerations, integrated pest management can be conceived as interactive systems with multiple levels of integration. Kogan (1988) proposed three different levels for insect pest management: (i) the integration of methods for the control of single species or species complexes (species/population level), (ii) the integration of impacts of multiple pest categories (insect, pathogen, and weeds) and the methods for their control (community level), and (iii) the integration of multiple pest impacts and the methods for their control at the total cropping system (agroecosystem level). A fourth level can be considered: the integration of social, political and legal constraints into integrated pest management (Kogan 1998).

Cumming and Spiesman (2006) have shown that, although integrated pest management was developed as a multiple level system and some area-wide pest management programs have known some success, integrated pest management has proceeded through an essay/error approach with few theoretical concerns (Kogan 1998) and especially without turning to theory developed in ecology. The integrated pest management paradigm would benefit from incorporating more ecological theory, particularly landscape ecology, into its foundation (Cumming and Spiesman 2006). They also argued that integrated pest management and habitat fragmentation control are two complementary aspects of the same problem. Crop protection strategy need no longer be a phytosanitary issue at the field scale and at a given moment, but could benefit from a more holistic approach at the farm and landscape levels. The link between landscape ecology theory and integrated pest management knowledge should enhance the effectiveness of integrated pest management especially management based on biological control. Landscape ecology theory brings a regional perspective to the integration of pest control strategies and it should lead us to a better understanding of the multi-scale relationships between the control of pest outbreaks and the larger landscape. This entails a real management of pest population in space and over time, taking into account cultivated and uncultivated habitat management (Ferron and Deguine 2005). Indeed, uncultivated habitats within the landscape have to be considered in integrated pest management strategies as they are key elements in providing ecological services. The development of an integrated pest management at a broader scale requires a thorough understanding of the cropping system effects on both pest and natural enemy populations and the spatial ecology of the given pest and beneficial species in order to maintain and optimise a

more complete range of ecological functions and ecosystem services within farming systems accounting for farmers' economical imperatives.

17.6.2 Methods of the Agronomist, a Complementary Approach Between Models, Diagnosis and Systems Experiments

17.6.2.1 General Framework for the Design of Innovative Cropping Systems

The elementary control methods of integrated pest management can be combined to control pest communities through integrated pest management strategies (Dhaliwal et al. 2004). The literature reveals that a single cultural practice given the pests and the objectives can lead to antagonistic effects. Nevertheless, the assessment of the combination of different control methods into crop management has received little attention and there is currently a lack of pesticide-free crop protection strategies in the case of oilseed rape. We present here a general methodological framework for designing innovative cropping systems and report the implications of reconsidering the scale for such an approach.

As explained earlier, designing cropping systems is a multi-objective task that has to consider a range of imperatives such as crop yield, environmental impacts, and farmers' incomes. In order to face the challenge of multi-functional and sustainable cropping systems, agronomists have developed a methodological framework to evaluate and conceive new cropping systems. Meynard et al. (2001) have developed a holistic approach which takes into account limiting factors of a given situation and thereby consider possible antagonist effects for designing and evaluating cropping systems (Fig. 17.1). In the case of pest management strategy, this methodological framework takes into account all pest damage of a given region and does not consider only one type of pest. The first step, the regional diagnosis step, is based on
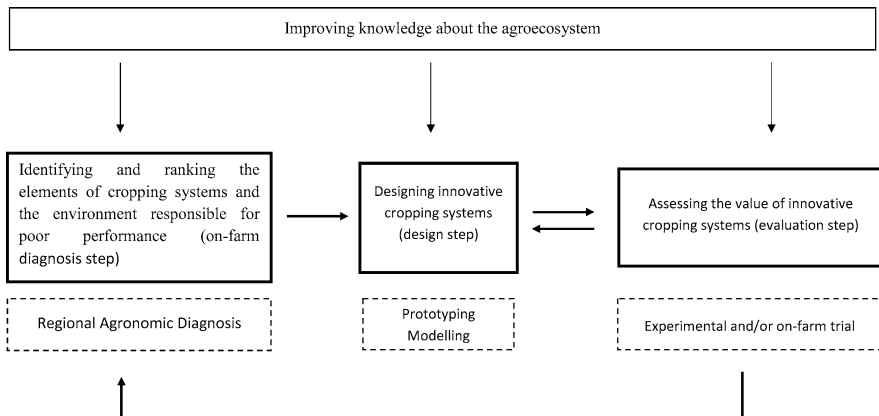
Fig. 17.1 Methodological framework for cropping system improvement (adapted from Meynard et al. 2001). The three iterative main steps of the general framework are in *bold lines*. The *dashed lines* indicate particular relevant examples of tools used at each step of the conception process

identifying and ranking the elements of the cropping systems and the environment responsible for poor performance. The second step consists in designing innovative cropping systems through different ways, such as prototyping or modelling. The last step is the evaluation step, which consists of assessing the value of the innovative cropping system.

17.6.2.2 The Regional Agronomic Diagnosis: A Pre-requisite for Designing Cropping System

The Regional Agronomic Diagnosis (RAD) proposed by Doré et al. (1997) aims to identify and rank the factors limiting crop yield on the regional scale, based on the study of a farmers' field network. The relevance of such a methodological framework has been demonstrated in various case studies (Doré et al. 2008). Weed biomass and nitrogen deficiencies linked to sowing date, soil management and the quantity of organic manure applied affecting organic winter oilseed rape (Valantin-Morison and Meynard 2008), nitrogen deficiencies linked to soil compaction affecting pea yield (Doré et al. 1997) and weed and nitrogen deficiencies linked to soil tillage, type of weed and crop density affecting yield performance (David et al. 2005), all provide good examples of major limiting factors identified by RAD. This type of approach is based on an analysis of the functioning of the agroecosystem and often helps to increase our knowledge about it. The RAD can be considered as a pre-requisite to the design of new cropping systems. Indeed, it allows us to rank the major pest problems and to identify the main crop practices, or cropping system elements that have to be considered. RAD thereafter focuses on the possible way to improve cropping systems and points out the knowledge that is required to achieve new crop management objectives. Nevertheless, considering that many environmental variables depend on processes operating at a scale larger than the field scale, Doré et al. (2008) in their review, suggested that the RAD requires adaptations, as the classical methodology does not take into account the surrounding environment in which a field is embedded. In fact, Valantin-Morison et al. (2007) in their study about the effect of cropping systems on pest damage to organic winter oilseed rape showed that surrounding environment variables can have an important explanatory role.

17.6.2.3 Prototyping and Modelling: Basis for Integrated Crop Management of Oilseed Rape Pests

Prototyping and modelling are two different and sometimes complementary ways for designing integrated crop management strategies. Vereijken (1997) formalized a methodical way of prototyping integrated and ecological arable farming systems founded on expert knowledge, which could be summarized by four main steps: (1) identifying the sets of constraints and establishing a hierarchy of objectives and criteria, (2) designing a theoretical prototype of the cropping system, based on a concerted action of an expert collective, that fits both with the multi-objective parameters imposed by the shortcomings of the current farming system in

a given region, and with the multi-constraints imposed by the whole environment, (3) improving the prototype on a few experimental and on-farm trials that represent the different constraints of the given region, and evaluating its performance through different criteria (such as crop performance, environmental, economical, or social), (4) adapting this cropping system prototype according to the multi-criteria evaluation. Iteration cycles between the two last steps lead to a technical prototype that could be tested in a larger range of situations in on-farm trials. Even if it has been proved that this method is very useful for designing a new cropping system (Lançon et al. 2007) and for involving different stakeholders, such as the researcher and the farmer, this type of approach has limits. Indeed, pedo-climatic variability is very difficult to take into account and the rules drawn up by the expert are sometimes not very formalized and are tough to evaluate and criticize.

Prototyping methodology and the modelling approach can be complementary. In fact, farm system models provide a means to expand, refine and formalize expert knowledge, as well as to integrate these and scientific agro-ecological knowledge at the farm level (Sterk et al. 2007). Traditionally, empirical approaches were often used to quantify economic threshold levels in decision-support systems for pest management. These empirical damage functions are generally derived by regression analysis relating a measurement of pest severity at a given crop stage to yield loss. But one of the main limits of such approaches is that they ignore crop-pest interactions and their value is generally limited to the local conditions where the measurements have been taken (Kropff et al. 1995). Moreover, the possible antagonist effects of crop practices on several pests are not considered with such an approach. Since then, a range of models that take into account pest life cycle, genotype, environment and/or management practices in designing crop management processes have been developed but mainly at the field level. For example, in the case of oilseed rape, a bio-economic model (OMEGAsys) has been developed to represent the effect of crop management either on crop yield, weed biomass, and stem canker attacks. The first aim of this model is to help in the conception of environmentally-friendly crop management at the field scale (Valantin-Morison et al. 2010). The output variables that are used to rank the different crop management strategies are attainable yield, frequency of pesticides treatments and gross margin. Some recent studies have reported an interest in using models to design new cropping systems for a range of problematics at a larger scale (Colbach et al. 2001a, b, Souchere et al. 2005, Tixier et al. 2007). Taking into account, to a greater extent, biological interactions in agroecosystems and their related scales raises some methodological issues. Indeed, given the considered spatial and time scales and the number of technical operations that have to be considered, it is sometimes very difficult to assess new pest management strategies using traditional field experiments. On these bases, spatial modelling appears to be a relevant tool for designing innovative cropping systems in which pest populations and incidence could be managed at such a scale. Experimental trials are used here to evaluate the relevance

of the cropping systems, improve their robustness, and their technical feasibility. The SIPPOM-WOSR model (Lô-Pelzer 2008) is a good example of the development of sustainable strategies to control a disease of the oilseed rape crop, phoma stem canker, at the regional scale. This model has been developed to evaluate the agronomic, economic, and environmental performances (through output variables such as disease severity indices and the associated yield losses, actual yields, gross margins, energetic costs of cultural practices and Treatment Frequency Indices) of spatially-distributed cropping systems that combine cultural, genetic, and chemical control. It also calculates the genetic structure of pathogen populations depending on evolutionary forces or genetic mechanisms: migration, selection and recombination. This model allows ranking integrated crop management strategies. It demonstrates that the spatial distribution of a specific resistant cultivar combined with other control methods (such as cultural and chemical) can enhance the durability of the specific resistance gene. For the moment no such modelling approach that integrates spatial distribution of cropping systems has been developed concerning insect pest management particularly those based on biocontrol.

However, a few models have been developed to investigate the interaction between crop and semi-natural habitat on natural enemy populations but with little concern on crop management effect. Halley et al. (1996) studied the role of landscape heterogeneity on linyphiid spiders and found that inclusion of a small amount of refuge areas in a cereal landscape increased the population size of spiders in fields, while pesticide use and crop rotation decreased population size. Bianchi et al. (2007) recently developed a spatially-explicit model that assesses the effect of land use (distribution of crop and semi-natural habitat, quality of crop habitat) on the population viability of the ladybeetle (*Coccinella septempunctata*) and the aphid population dynamics in the agricultural landscape. The authors found that the primary cause of the decline of ladybeetles in Czech landscapes is the decrease of aphid populations in alfalfa and cereal crops due to a major reduction in fertilizer input from 1978 to 2005. This model demonstrates that the population viability of the ladybeetle depends on the availability of aphid prey in crops (particularly cereal) distributed in the landscape.

It is important to highlight that designing cropping systems through modelling is only possible after preliminary studies on the effects of cropping systems and landscape elements on pest populations and their natural enemies. Knowledge about their biology and ecology is also required. For example, Gu et al. (2007) explain that the deployment of integrated pest management at a larger scale requires that particular attention be paid to: (i) winter breeding areas and the dynamics of overwintering populations, (ii) the pattern of spring migration and seasonal variations in the population distribution areas, (iii) the relationship between incidence of migration events and weather systems, and (iv) the contribution of migrant populations to local infestations. Models are able to integrate very different pieces of knowledge and are therefore useful tools for understanding complex agroecological interactions occurring in rural landscapes and for identifying crucial knowledge gaps.

17.7 Conclusion

The development of sustainable agricultural systems is now a major concern of many researchers, farmers, and policymakers worldwide. One of the key strategies in sustainable cropping systems is to restore and maximize ecosystem services in agricultural landscapes. Improving biological control appears to be the cornerstone of insect pest management. This review provides clear evidence that the development of integrated pest management needs to take into account various aspects, such as ecological, agronomical or socio-economical ones and different spatial or temporal scales. Linking integrated insect pest management and landscape ecology requires more studies to investigate the effects of landscape composition on interactions between natural enemies, pests, and crop productivity. It is clear that, although there are numerous (and rapidly increasing) studies showing that the biological control of pests is technically possible, via new crop management systems or habitat management, the economic efficiency of this biological control remains to be demonstrated. Moreover, consideration of relevant crop management effects at the landscape scale will certainly allow a better discrimination and identification of the semi-natural habitat effects and the cropping system effects on natural enemies and pest populations.

The development of area-wide pest management requires a more holistic approach that would integrate crop and landscape management effects. It would also fill gaps in knowledge about the ecology of insect pests (e.g., overwintering areas, pattern of migration) and quantify those effects in terms of environmental (e.g., energy use, pesticides use, nitrogen discharge) and economical consequences (e.g., crop damage, yield losses, cost/benefit). In order to meet such a scientific challenge, complementing on-farm trials that produce knowledge and improve cropping systems or scenarios with modelling approaches is likely to be a potentially productive approach.

Moreover, designing innovative cropping systems with more reliance on biological control requires that all stakeholders be consulted. Indeed, development of an integrated pest management at the landscape scale needs, on the one hand, solid scientific knowledge, and on the other hand, a good synergy between the different stakeholders, such as farmers, policy makers, and managers or private land owners. This synergy could be used to implement integrated pest management on a wider scale.

The review of studies on the integration of crop and landscape management into new crop protection strategies has led us to conclude that further investigations are required on different key fronts: (i) knowledge production on cropping system effect and ecosystem production functions and services, (ii) improving knowledge about pest and natural enemy ecology, (iii) designing innovative cropping systems, and (iv) implementing and adapting these in diverse biophysical and social contexts.

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