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Integrated Management of *Helicoverpa armigera* in Soybean Cropping Systems

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1. Introduction

In most developing countries, agriculture is the driving force for broad-based economic growth and low agricultural productivity is a major cause of poverty, food insecurity, and malnutrition. However, food production per unit of land is limited by many factors, including fertilizer, water, genetic potential of the crop and the organisms that feed on or compete with food plants. Despite the plant-protection measures adopted to protect the principal crops, 42.1% of attainable production is lost as result of attack by pests [1]. Therefore, accelerated public investments are needed to facilitate agricultural growth through high-yielding varieties with adequate resistance to biotic and abiotic stresses, environment-friendly production technologies, availability of reasonably priced inputs in time, dissemination of information, improved infrastructure and markets, and education in basic health care.

Soybean (*Glycine max* (L.) Merrill) is one of the most important and widely grown oil seed crops in the world. Successful production in soybean cropping systems is hampered due to the incidence of several insect pests such as *Etiella zinkienella* Treitschke, *Tetranychus urticae* Koch, *Thrips tabaci* Lindeman, *Spodoptera exigua* (Hübner) and *Helicoverpa armigera* (Hübner) [2-9]. Among these pests, *H. armigera* represents a significant challenge to soybean production in different soybean-growing areas around the world. *Helicoverpa armigera* is an important pest of many crops in many parts of the world and is reported to attack more than 60 plant species belonging to more than 47 families (such as soybean, cotton, sorghum, maize, sunflower, groundnuts, cowpea, tomato and green pepper) [10-12]. This noctuid pest is distributed eastwards from southern Europe and Africa through the Indian subcontinent to Southeast Asia, and thence to China, Japan, Australia and the Pacific Islands [13]. The pest status of this species can be derived from its four life history characteristics (polyphagy, high mobility, high fecundity and a facultative diapause) that enable it to survive in unsta-

ble habitats and adapt to seasonal changes. Direct damage of the larvae of this noctuid pest to flowering and fruiting structures together with extensive insecticide spraying resulted in low crop yield and high costs of production [14].

Different methods have been applied to control *H. armigera* in order to improve the quality and quantity of soybean production in cropping systems of this oil seed crop. However, synthetic insecticides including organophosphates, synthetic pyrethroids and biorational compounds are the main method for *H. armigera* control in different parts of the world. This wide use of pesticides is of environmental concern and has repeatedly led to the development of pesticide resistance in this pest. Furthermore, the deleterious effects of insecticides on nontarget organisms including natural enemies are among the major causes of pest outbreaks. It is therefore necessary to develop a novel strategy to manage population of *H. armigera* and reduce the hazardous of synthetic chemicals.

The common trend towards reducing reliance on synthetic insecticides for control of insect pests in agriculture, forestry, and human health has renewed worldwide interest in integrated pest management (IPM) programmes. IPM is the component of sustainable agriculture with the most robust ecological foundation [15]. IPM not only contributes to the sustainability of agriculture, it also serves as a model for the practical application of ecological theory and provides a paradigm for the development of other agricultural system components. The concept of IPM is becoming a practicable and acceptable approach among the entomologists in recent past all over the world and focuses on the history, concepts, and the integration of available control methods into integrated programmes. However, this approach advocates an integration of all possible or at least some of the known natural means of control with or without insecticides so that the best pest management in terms of economics and maintenance of pest population below economic injury level (EIL) is achieved.

Fundamental of effective IPM programmes is the development of appropriate pest management strategies and tactics that best interface with cropping system-pest situations. Depending on the type of pest, however, some of the primary management strategies could be selected. In the case of *H. armigera*, several management tactics should be considered to implement a comprehensive integrated management. Potential of some of the control tactics to reduce population density of *H. armigera* in different cropping systems were evaluated by several researchers and attempts have been made to develop integrated management approach for *H. armigera* using host plant resistance [2, 4, 6, 11] including transgenic Bt crops [16], biological control (predators and parasitoids) [17], interference methods including sex pheromones [18], biopesticides (especially commercial formulations of *Bacillus thuringiensis*) [19], cultural practices (including appropriate crop rotations, trap crops, planting date and habitat complexity) [20] and selective insecticides [21]. Likewise there remains a need for ongoing research to develop a suite of control tactics and integrate them into IPM systems for sustainable management of *H. armigera* in cropping systems. Keeping this in view, integration of these methods based on the ecological data especially thermal requirements of this pest and its crucial role in forecasting programme of *H. armigera* could lead a successful integrated management for this pest in soybean cropping systems.

As discussed above, integrated management is typically problematic in cropping systems, especially in the case of *H. armigera* on soybean. However, our intent in this section is not to develop an exhaustive review of all resources that may possibly contribute to more effective pest management for the future, but to select several topic areas that will make essential contributions to sustainable soybean cropping systems. Although the past research focused on developing various pest management tactics that would be packaged into an integrated pest management strategy, we have selected several types of resources for our discussions, realizing that there are other resources can be used in developing IPM programmes. Furthermore, to generate a comprehensive management programme, we present our perspectives on future research needs and directions for sustainable management of this pest in soybean cropping systems such as tri-trophic interactions [22], importance of modeling of insect population [23], crucial role of forecasting and monitoring programmes in IPM [24], interactions among different management tactics in IPM [25] and significance of biotechnology and genetically modified plants in IPM. Therefore, considering the importance of *H. armigera* in successful production of soybean, this review intends to provide an appropriate document to the scientific community for sustainable management of *H. armigera* in soybean cropping systems.

2. History of terminology and definition of IPM

Although many IPM programmes were initiated in the late 1960s and early 1970s in several parts of the world, it was only in the late 1970s that IPM gained momentum [26]. Throughout the late 19th and early 20th centuries, in the absence of powerful pesticides, crop protection specialists relied on knowledge of pest biology and cultural practices to produce multi tactical control strategies that, in some instances, were precursors of modern IPM systems [27]. That stance changed in the early 1940s with the advent of organosynthetic insecticides when protection specialists began to focus on testing chemicals, to the detriment of studying pest biology and non-insecticidal methods of control [15]. The period from the late 1940s through the mid-1960s has been called the dark ages of pest control. By the late 1950s, however, warnings about the risks of the preponderance of insecticides in pest control began to be heard. The publication of the book "Silent Spring" by Rachael Carson in 1962 ignited widespread debate on the real and potential hazards of pesticides. This still ongoing dialogue includes scientists in many disciplines, environmentalists, and policy makers. However, "Silent Spring" contributed much to the development of alternatives to pesticides for pest management purposes, augmented global interests in developing cropping systems that limit crop pests, and added much to the environmental movement [26]. In fact, widespread concerns about the detrimental impact of pesticides on the environment and related health issues were responsible in large part for the development of the concept of IPM.

The seed of the idea of integrated control appears in a paper by Hoskins *et al.* [28]. Conceivably, "integrated control" was uttered by entomologists long before formally appearing in a publication. However, it was the series of papers starting with Smith and Allen [29] that established integrated control as a new trend in economic entomology. Towards the end of the 1960s, integrated control was well entrenched both in the scientific literature and in the prac-

tice of pest control, although by then “pest management” as a sibling concept was gaining popularity [30]. However, in subsequent publications, integrated control was more narrowly defined as “applied pest control which combines and integrates biological and chemical control”, a definition that stood through much of the late 1950s and the early 1960s but began to change again in the early 1960s as the concept of pest management gained acceptance among crop protection specialists [15, 26].

The concept of “protective population management”, later shortened to “pest management”, gained considerable exposure at the twelfth International Congress of Entomology, London [31]. The Australian ecologists who coined the expression contended that “control”, as in pest control, subsumes the effect of elements that act independently of human interference. Populations are naturally controlled by biotic and abiotic factors, even if at levels intolerable to humans. Management, on the other hand, implies human interference. Although the concept of pest management rapidly captured the attention of the scientific community, in 1966 Geier seemed to minimize the semantic argument that favored “pest management” by stating that the term had no other value than that of a convenient label coined to convey the idea of intelligent manipulation of nature for humans’ lasting benefit, as in “wildlife management” [32].

Not until 1972, however, were “integrated pest management” and its acronym IPM incorporated into the English literature and accepted by the scientific community. In creating the synthesis between “integrated control” and “pest management”, no obvious attempt was made to advance a new paradigm. Much of the debate had been exhausted during the 1960s and by then there was substantial agreement that: (a) “integration” meant the harmonious use of multiple methods to control single pests as well as the impacts of multiple pests; (b) “pests” were any organism detrimental to humans, including invertebrate and vertebrate animals, pathogens, and weeds; (c) “management” referred to a set of decision rules based on ecological principles and economic/social considerations and (d) “IPM” was a multidisciplinary endeavor.

The search for a perfect definition of IPM has endured since integrated control was first defined. A survey recorded 65 definitions of integrated control, pest management, or integrated pest management [26]. Unfortunately, most of them perpetuate the perception of an entomological bias in IPM because of the emphasis on pest populations and economic injury levels, of which the former is not always applicable to plant pathogens, and the latter is usually attached to the notion of an action threshold often incompatible with pathogen epidemiology or many weed management systems [33]. Furthermore, most definitions stress the use of combination of multiple control methods, ignoring informed inaction that in some cases can be a better IPM option for arthropod pest management [15]. It was, however, in 1972 that the term ‘integrated pest management’ was accepted by the scientific community, after the publication of a report under the above title by the Council on Environmental Quality [34]. Much of the debate had already taken place during the 1960s and by then there was substantial agreement on the following issues [15]: (a) the appropriate selection of pest control methods, used singly or in combination; (b) the economic benefits to growers and to society; (c) the benefits to the environment; (d) the decision rules that guide the selection of the control action and (e) the need to consider impacts of multiple pests.

Several authors have come close to meeting the criteria for a good definition, but a consensus is yet to be reached. Accordingly, some of the IPM definitions were listed in Table 1. A broader definition was adopted by the FAO Panel of Experts [35]: “Integrated Pest Control is a pest management system that, in the context of the associated environment and the population dynamics of the pest species, utilizes all suitable techniques and methods in as compatible a manner as possible and maintains the pest population at levels below those causing economic injury.” This definition has been cited frequently and has served as a template for others. However, based on an analysis of definitions spanning the past 35 years, the following is offered in an attempt to synthesize what seems to be the current thought: “IPM is a decision support system for the selection and use of pest control tactics, singly or harmoniously coordinated into a management strategy, based on cost/benefit analyses that take into account the interests of and impacts on producers, society, and the environment” [15].

| Definition | Reference |
|---|-------------------------------|
| IPM refers to an ecological approach in pest management in which all available necessary techniques are consolidated in a unified programme, so that pest populations can be managed in such a manner that economic damage is avoided and adverse side effects are minimized. | [36] |
| IPM is a multidisciplinary ecological approach to the management of pest populations, which utilizes a variety of control tactics compatibly in a single coordinated pest-management system. In its operation, integrated pest control is a multi-tactical approach that encourages the fullest use of natural mortality factors, complemented, when necessary, by artificial means of pest management. | [37] |
| IPM is a pest population management system utilizes all suitable techniques in a compatible manner to reduce pest populations and maintain them at levels below those causing economic injury. | [38] |
| IPM is a systematic approach to crop protection that uses increased information and improved decision-making paradigms to reduce purchased inputs and improve economic, social and environment conditions on the farm and in society. | [39] |
| IPM is a comprehensive approach to pest control that uses combined means to reduce the status of pests to tolerable levels while maintaining a quality environment. | [40] |
| IPM is an intelligent selection and use of pest-control tactics that will ensure favourable economic, ecological and sociological consequences. | [41] |
| IPM is a sustainable approach that combines the use of prevention, avoidance, monitoring and suppression strategies in a way that minimizes economic, health and environmental risks. | [42] |
| IPM is a decision support system for the selection and use of pest control tactics, singly or harmoniously coordinated into a management strategy, based on cost/benefit analyses that take into account the interests of and impacts on producers, society, and the environment. | [15] |
| IPM is a dynamic and constantly evolving approach to crop protection in which all the suitable management tactics and available surveillance and forecasting information are utilized to develop a holistic management programme as part of a sustainable crop production technology. | [43] |
| IPM is a systemic approach in which interacting components (mainly control measures) act together to maximize the advantages (mainly producing a profitable crop yield) and minimize the disadvantages (mainly causing risk to human and environment) of pest control programmes. | [The authors of this chapter] |

Table 1. Some of the proposed definitions for IPM

3. Systems in agriculture and the situation of IPM as a sub-system

Spedding [44] defined a system as a group of interacting components, operating together for a common purpose, capable of reacting as a whole to external stimuli. A system is unaffected by its own output and has a specified boundary based on the inclusion of all significant feedbacks. However, four types of systems are generally acknowledged in agriculture including ecosystem, agroecosystem, farming systems and cropping systems (Figure 1). In this hierarchy, a system may consist of several sub-systems. IPM is a sub-system of cropping system and considered as the operating system used by farmers to manage population of crop pests. This sub-system has a degree of independence and can be studied in isolation of the cropping system. It has its own inputs and has the same output as the main system (i. e. yield) but relates to only some of the components and therefore, to only some of the inputs [45].

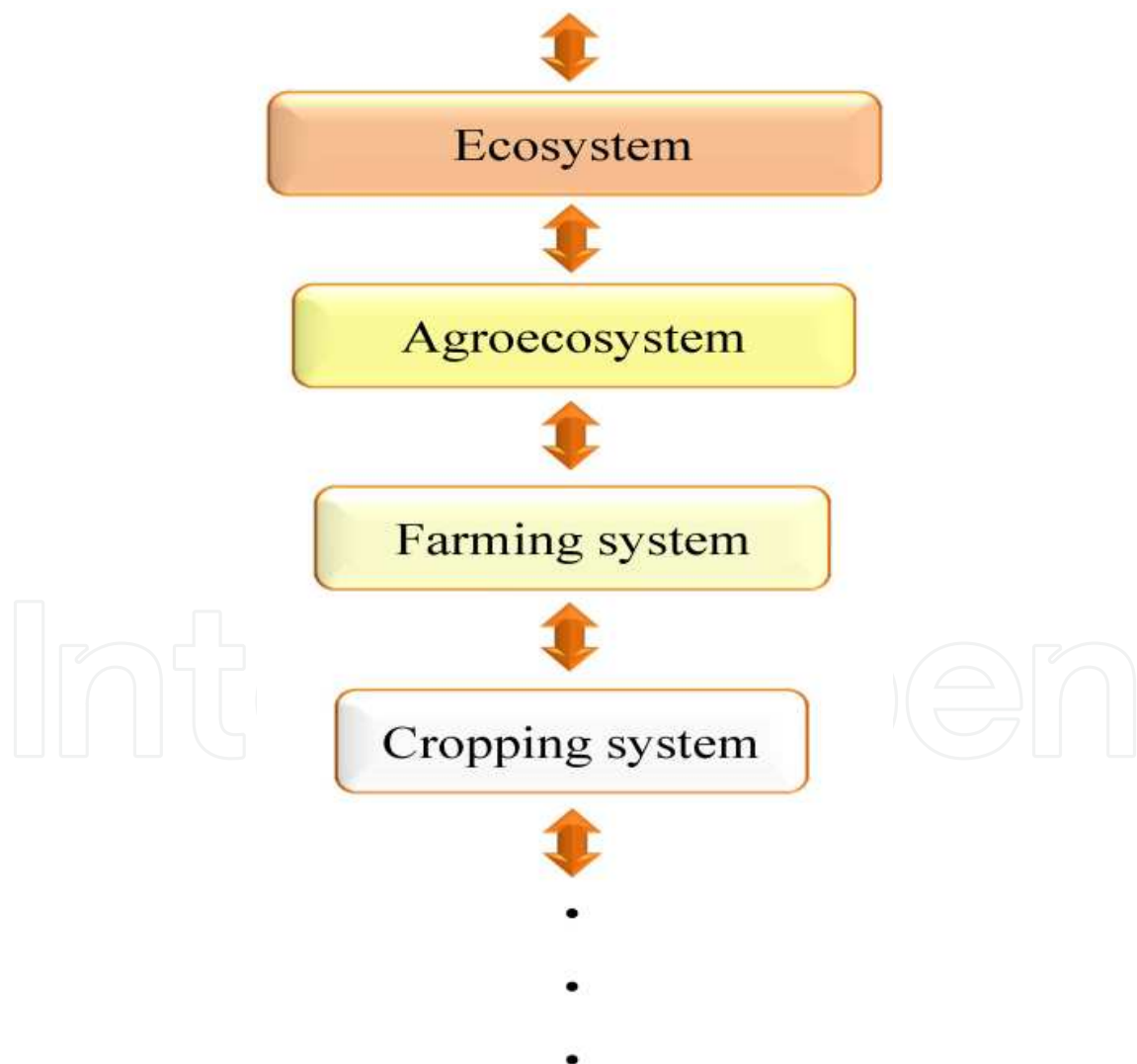


Figure 1. A hierarchy of systems in agriculture

IPM systems have a goal of providing the farmer with an economic and appropriate means of controlling crop pest. The aim should be to devise an IPM system which is sufficiently robust to maintain control over a prolonged period of time [46]. However, to achieve an IPM system a number of attributes will require including: (a) provide effective control of pest; (b) be economically viable; (c) simplicity and flexibility; (d) utilize compatible control measure; (e) sustainability and (f) minimum harmful effect on the environment, producer and consumer.

First and foremost the IPM system must be effective. For the farmer this means that this system should be at least as good as the conventional control methods. The system should be economic. No farmer will adopt and sustain use of uneconomic pest management practices. On the other hand, an IPM system must be designed to be as simple as possible, utilizing the minimum number of control measures compatible with maintaining pest populations at appropriate levels. The individual control measures should of course be compatible and optimize natural mortality factors. It is important during design of an IPM system to consider the level of control which is required and the best mix of control measures that will achieve this with minimal antagonism. Finally, the IPM system should be sustainable, have minimum impact on the environment and present no hazard to the farmer, their families or the consumers of the crop products [45].

4. Decision making in IPM

Following widespread concerns about the adverse effects of insecticides it became clear that calendar spraying was not the appropriate approach to pest control. In fact, determining whether an insect control measure (usually an insecticide) is “needed” is one of the basic principles of any IPM programme. “Need” can be defined in a number of ways, but most growers associate the need for an insecticide with economics. In other words, most growers ask some form of these questions: “How many insects cause how much damage?”, “Are the damage levels all significant?” and “Will the value of yield protection with an insecticide offset the cost of control?” Therefore, researchers from different agricultural disciplines came to realize that a decision rule or threshold should answer such questions and that pest control must be viewed as a decision making process (Figure 2).

Pest management is a combination of processes that include obtaining the information, decision making and taking action [41]. In assessing, evaluating and choosing a particular pest control option, farmer’s perception of the problem and of potential solutions is the most important factor (Figure 2). Decision making in pest management, like other economic problems in agriculture, involves allocating scarce resources to meet food demand of a growing population. In this process, agricultural producers have to make choices regarding the use of several inputs including labor, insecticides, herbicides, fungicides, and consulting expenses related to the level and intensity of pest infestation and the timing of treatment. However, decision making process for pest control takes place in many levels at the fields. These various layers of decision making affect the whole strategy of pest control in a given cropping

system, region or country as well as the set of approaches and measures that are chosen to implement pest control programmes.

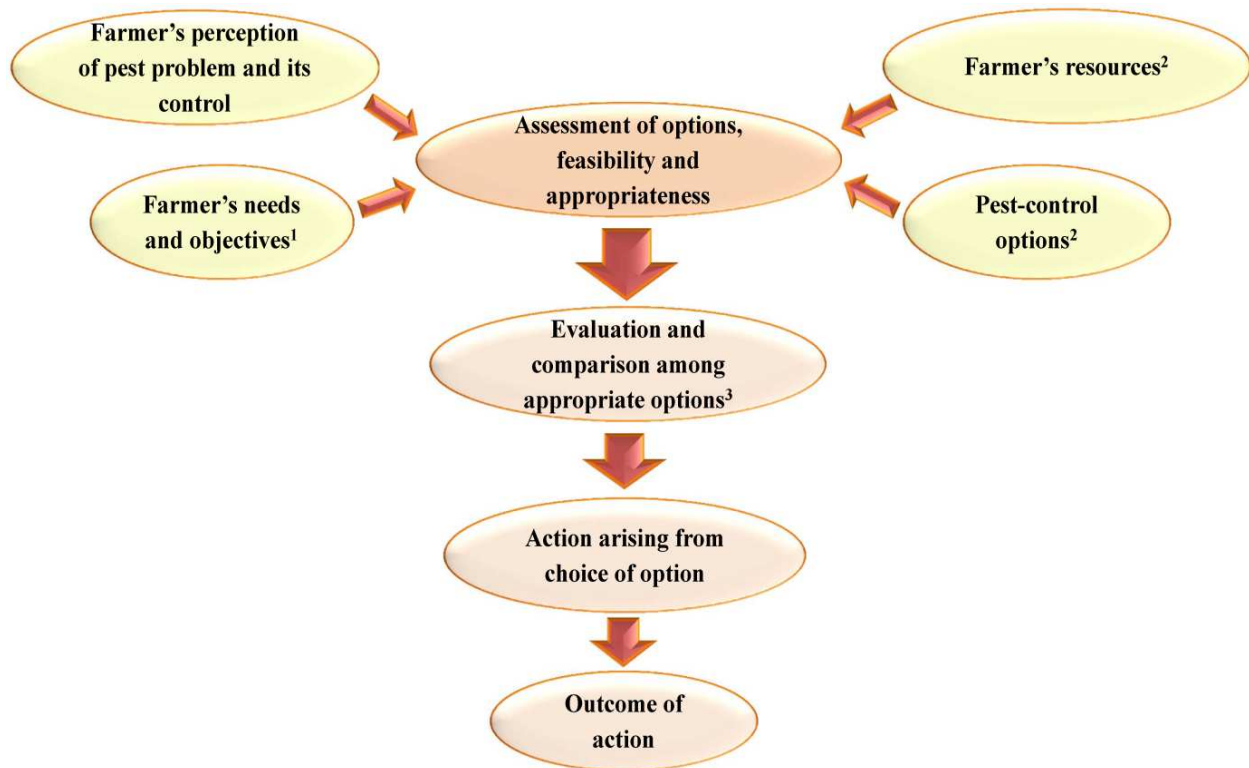


Figure 2. The process of decision making in IPM. (after Reichelderfer *et al.* [47]) 1. The way in which control options are assessed will depend on the farmer's objectives. Subsistence farmers may select for a guaranteed food supply, while commercial farmers are more concerned with profit. 2. The number of options that a farmer can feasibly use will depend on the constraints set by the resources available. 3. Compare the cost-effectiveness of alternative practices.

5. Crucial role of economic thresholds for implementation of IPM programmes

In most situations it is not necessary, desirable, or even possible to eradicate a pest from an area. On the other hand, the presence of an acceptable level of pests in a field can help to slow or prevent development of pesticide resistance and maintain populations of natural enemies that slow or prevent pest population build-up. Therefore, the concepts of economic injury level (EIL) and economic threshold (ET [sometimes called an action threshold]) were developed (Figure 3). EIL and ET constitute two basic elements of the IPM [48]. Economic injury level was defined as the lowest population density that will cause economic damage [49]. The EIL is the most essential of the decision rules in IPM. In addition, the economic injury level provides an objective basis for decision making in pest management and the backbone for the management of pests in an agricultural system is the concept of EIL [48]. Ideally, an EIL is a scientifically determined ratio based on results of replicated research tri-

als over a range of environments. In practice, economic injury levels tend to be less rigorously defined, but instead are nominal or empirical thresholds based on grower experience or generalized pest-crop response data from research trials. Although not truly comprehensive, such informal EILs in combination with regular monitoring efforts and knowledge of pest biology and life history provide valuable tools for planning and implementing an effective IPM programme. However, because growers will generally want to act before a population reaches EIL, IPM programmes use the economic threshold (Figure 3). The concept of economic threshold implies that if the pest population and the resulting damage are low enough, it does not pay to take control measures. In practice, the term economic threshold has been used to denote the pest population level at which economic loss begins to occur and indicate the pest population level at which pest control should be initiated [50].

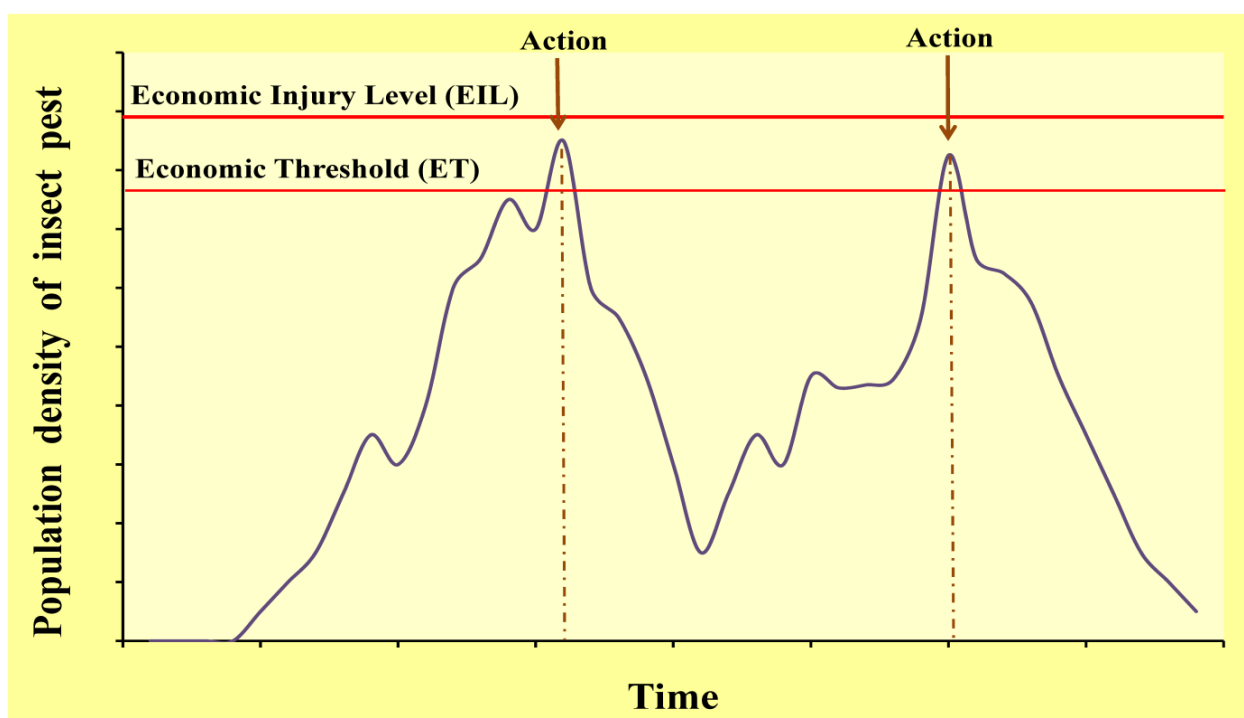


Figure 3. Graph showing the relationship between the economic threshold (ET) and economic injury level (EIL). The arrows indicate when a pest control action is taken.

5.1. EIL and ET for *H. armigera* on different crops

Economic injury level and economic threshold of *H. armigera* on some crops was estimated by several researchers (Table 2). In the case of *H. armigera* on soybean, these thresholds are poorly defined and a little information in this regard is available. However, economic thresholds; especially economic injury level; are dynamic and can be varied from year to year or even from field to field within a year depending on crop variety, market conditions, development stages of plant, available management options, crop value and management costs (Table 2).

| Crop | Economic threshold (ET) | Economic Injury Level (EIL) | References |
|------------|-----------------------------|-----------------------------|------------|
| Chickpea | - | > 4 larvae / m ² | [51] |
| Chickpea | - | 1.0 larva / m row | [52] |
| Chickpea | 1.0 larva / m row | - | [53] |
| Chickpea | - | 1 larva / 10 plants | [54] |
| Chickpea | - | 0.6 larva / plant | [55] |
| Chickpea | 1.77 - 2.00 larvae / m row | - | [56] |
| Chickpea | - | 1.0 larva / m row | [57] |
| Chickpea | 0.81 larva / m row | 1.1 larva / m row | [58] |
| Pigeon pea | - | 0.78-0.80 larvae / plant | [59] |
| Tomato | 1.0 larva / plant | - | [60] |
| Cotton | - | 19.86 larvae / 100 plants | [61] |
| Mung bean | 1-3 larvae / m ² | - | [62] |
| Peanuts | 4 larvae / m ² | - | [62] |
| Soybean | - | 8 larvae / m ² | [63] |

Table 2. Economic threshold (ET) and Economic injury level (EIL) of *Helicoverpa armigera* on different crops.

6. Monitoring activity in integrated management of *H. armigera*

In an IPM programme, pest managers use regular inspections, called monitoring, to collect the information they need to make appropriate decisions. A central idea in IPM is that a treatment is only used when pest numbers justify it, not as a routine measure. Keeping this in view, in IPM programmes, chemical control is applied only after visual inspection or monitoring devices indicate the presence of pests in that specific area, the pest numbers have exceeded the economic threshold (ET) and adequate control cannot be achieved with non-chemical methods within a reasonable time and cost. Therefore, it was considered that monitoring could reduce spraying costs by withholding a spray until a given threshold is reached [64].

For many years, light traps have been used to monitor *Helicoverpa* moth populations. Hartstack *et al.* [65] developed a model for estimating the number of moths per hectare from these light-trap catches, to evaluate the possible use of light traps for controlling *Helicoverpa*

spp. Walden [66] presented the first comprehensive report on seasonal occurrence and abundance of the *Helicoverpa zea* (Boddie), based on light trap collections. Beckham [67] used light traps to index the populations of *Helicoverpa* spp. and reported that a significantly lower percentage of the *Helicoverpa virescens* (Fabricius) populations responded to black-light lamps in traps than did *H. zea*.

In the last few years, pheromone traps (containing virgin females or synthetic pheromones) have replaced light traps as moth-monitoring devices. These traps provide the pest manager with a convenient and effective tool for monitoring adult moth [68]. However, pheromone traps are highly efficient, simple to construct, inexpensive, and portable (requiring no power). Furthermore, only the single species for which the trap is baited is attracted and caught, making identification and counting quick and easy. As an added bonus, pheromone traps also detect spring emergence of moths 2 or 3 weeks earlier than light traps, which should give more precision to forecasts.

Several group of researchers made the comparison of indexing populations of *Helicoverpa* spp. in light traps versus pheromone traps. Their results revealed that light trap catches may index seasonal fluctuation of populations more accurately than pheromone traps, however, pheromone traps are more sensitive to low populations early in the season and decline in efficiency with high populations late in the season [69].

There has been a considerable improvement into synthesis of the pheromones of *Helicoverpa* spp. in recent years. However, preliminary studies have already revealed that the catches in pheromone traps do not correlate very well with light-trap catches and field counts of the pest in all circumstances. In fact, trap catch data do not provide a quantitative threshold for intervention because a relationship between catch number and subsequent crop damage has proved to be lacking in most cases [70].

Egg count provides a better quantitative threshold for monitoring activity of *H. armigera* but egg desiccation, egg infertility or egg parasitism (biasing data) together with skill needed for field scouting, too often promote weak correlations between egg number and larval damage [71]. On the other hand, fruit inspection in the field has proved to be a valuable tool when developed against a number of fruit damaging pest species including *H. armigera* [72]. The major advantage of thresholds based on fruit inspection is that the short time between plant scouting for larval injury and fruit damage greatly increases correlation between both of these variables. Moreover, damaged fruit-count-based decision making may also be easily learned and carried out by growers [70].

Finally, we must now determine whether these pheromone traps are going to be of practical value in *Helicoverpa* management. For this, there is first a need to standardize trap design, pheromone dosage and release rates from the chosen substrate, and siting of the traps. As the next step, catches in these traps should be compared with other measures of *Helicoverpa* populations (light traps and actual counts of *Helicoverpa* eggs/larvae on the host plants in the same area). However, data from pheromone traps have already been shown to be valuable in some studies in the USA, where the data have been used in prediction models and have given useful information on the timing of infestations [64].

7. Importance of thermal modeling in successful implementation of integrated management of *H. armigera*

For decades, models have been an integral part of IPM. For instance, the use of models has helped pest managers decide how the agroecosystem should be changed to favor economy and conservation and not to favor pests. Moreover, models have allowed scientists to conduct simulated experiments when the conduct of those experiments would not have been possible. Furthermore, models have been used whenever scientists wanted to explore as well as understand the complexities of agroecosystems [26, 73, 74]. However, among the different types of models developed for implication of IPM programmes, forecasting models (especially thermal models) have a highlighted situation. Understanding the factors governing the pest development and implementing this knowledge into forecast models enable effective timing of interventions and increases efficacy and success of control measures [74]. For a pest manager, being able to predict abundance and distribution of a pest species, and its timing and level, is crucial to both strategic planning and tactical decision making. Thermal models, based on insect physiological time-scales, have been relatively successful at predicting the timing of population peaks and are useful for timing sampling and control measures.

Temperature is a critical abiotic factor influencing the dynamics of insect pests and their natural enemies [75-77]. Temperature has a direct influence on the key life processes of survivorship, development, reproduction, and movement of poikilotherms and hence their population dynamics [78]. The importance of predicting the seasonal occurrence of insects has led to the formulation of many mathematical models that describe developmental rates as a function of temperature [79]. Thermal models have been developed for insect pests to predict emergence of adults from the overwintering generation, eclosion of eggs, larval and pupal development, and generation time. These models, all based on a linear relationship between temperature and developmental rate, have been used with varying degrees of success to time pesticide application for pest control [80]. However, linear approximation enables the estimation of lower temperature thresholds (T_{min}) and thermal constants (K) within a limited temperature range and to describe the developmental rate more realistically and over a wider temperature range, several nonlinear models have been applied [74, 76]. These nonlinear models provide value estimates of lower and upper temperature thresholds and optimal temperature for development of a given stage.

Several studies have been conducted on the effects of temperature on developmental time of *H. armigera* reared on host plant materials or artificial diets [81, 82]. In a recent study by Mironidis and Savopoulou-Soultani [83], a comprehensive analysis of survivorship and development rates at all life stages of *H. armigera* reared under constant and corresponding alternating temperatures regimes was performed (some of the most important results are listed in Tables 3 and 4).

| Stage | Temperature | Lower temperature threshold (T_{min} °C) | Thermal constant ^a (K DD) |
|-----------------------|-------------|--|---|
| Egg | Constant | 11.95 | 39.68 |
| | Alternating | 5.53 | 57.47 |
| Larva | Constant | 10.52 | 238.09 |
| | Alternating | 2.17 | 416.16 |
| Pupa | Constant | 10.17 | 192.30 |
| | Alternating | 1.06 | 285.71 |
| Total immature stages | Constant | 9.57 | 476.19 |
| | Alternating | 2.23 | 769.23 |

^a Cumulative degree-day (DD) required for stage development

Table 3. Lower temperature threshold and thermal constant of different life stages of *Helicoverpa armigera* (after Mironidis and Savopoulou-Soultani [83]).

The results obtained by Mironidis and Savopoulou-Soultani [83] revealed that over a wide constant thermal range (15-27.5°C) total survivorship is stable and apparently not affected by temperature. Below 15°C, survivorship decreased rapidly, reached zero at 12.5°C. At higher temperatures, survivorship also decreased very quickly above 28°C and fell to zero at 40°C. Furthermore, their results showed that *H. armigera*, when reared at constant temperatures, could not develop from egg to adult stage (capable of egg production) out of the temperature range of 17.5-32.5°C. Nevertheless, alternating temperatures allowed *H. armigera* to complete its life cycle over a much wider range, 10-35°C, compared with constant temperatures.

| Stage | Temperature | Lower temperature threshold (T_{min} °C) | Optimal temperature (T_{opt} °C) | Upper temperature threshold (T_{max} °C) |
|-----------------------|-------------|--|--|--|
| Egg | Constant | 10.58 | 34.84 | 39.99 |
| | Alternating | 2.33 | 39.26 | 40.56 |
| Larva | Constant | 11.17 | 34.22 | 39.11 |
| | Alternating | 1.55 | 39.35 | 40.95 |
| Pupa | Constant | 12.31 | 35.37 | 40.00 |
| | Alternating | 1.01 | 41.92 | 43.54 |
| Total immature stages | Constant | 9.42 | 34.61 | 39.81 |
| | Alternating | 1.85 | 42.35 | 42.92 |

Table 4. Lower temperature threshold, optimal temperature and upper temperature threshold of different life stages of *Helicoverpa armigera* obtained by nonlinear Lactin model (after Mironidis and Savopoulou-Soultani [83]).

In another study, temperature-dependent development of *H. armigera* was studied in the laboratory conditions at eight constant temperatures (15, 17.5, 20, 22.5, 25, 30, 32.5 and 35°C) [Adigozali and Fathipour, unpublished data]. In this study, two linear (Ordinary linear and Ikemoto and Takai) and 9 nonlinear (Briere-1, Briere-2, Lactin-1, Lactin-2, Polynomial, Kontodimas-16, Analytis-1, Analytis-2 and Analytis-3) models were fitted to describe development rate of *H. armigera* as a function of temperature. The lower temperature threshold and thermal constant of different life stages of *H. armigera* estimated by linear models are listed in Table 5. The obtained results revealed that both models have acceptable accuracy in prediction of T_{min} and K for different life stages of *H. armigera* [Adigozali and Fathipour, unpublished data].

| Stage | Model | Lower temperature threshold (T_{min} °C) | Thermal constant (K DD) |
|-----------------------|-------------------|--|----------------------------|
| Egg | Ordinary linear | 8.61 | 47.85 |
| | Ikemoto and Takai | 9.52 | 44.60 |
| Larva | Ordinary linear | 6.07 | 367.65 |
| | Ikemoto and Takai | 7.18 | 343.00 |
| Pre-pupa | Ordinary linear | 11.70 | 42.55 |
| | Ikemoto and Takai | 10.80 | 46.70 |
| Pupa | Ordinary linear | 14.29 | 132.28 |
| | Ikemoto and Takai | 13.20 | 150.00 |
| Total immature stages | Ordinary linear | 10.39 | 561.78 |
| | Ikemoto and Takai | 10.30 | 566.00 |

Table 5. Lower temperature threshold and thermal constant of different life stages of *Helicoverpa armigera* estimated by Ordinary linear and Ikemoto and Takai models.

According to results obtained by Adigozali and Fathipour [unpublished data], of the nonlinear models fitted, the Lactin-2, Lactin-2, Polynomial, Polynomial and Briere-2 models were found to be the best for modeling development rate of egg, larva, pre-pupa, pupa and total immature stages of *H. armigera*, respectively (Table 6). However, estimated values for crucial temperatures of different life stages of *H. armigera* by Adigozali and Fathipour [unpublished data] conflict with those reported by Mironidis and Savopoulou-Soultani [83] (Tables 3-6). Some possible reasons for these disagreements are: physiological difference depending on the food quality, genetic difference as a result of laboratory rearing and techniques/equipment of the experiments. In general, the results obtained from constant temperature experi-

ments are often not applicable directly to the field where pests are subjected to diurnal variation of temperature and such information need to be validated under fluctuating temperatures before using for predictive purpose in the field. Finally, such data provide fundamental information describing development of *H. armigera*, when this information to be used in association with other ecological data may be valuable in integrated management of this noctuid pest in soybean cropping systems.

| Stage | Model | Optimal temperature (T_{opt} °C) | Upper temperature threshold (T_{max} °C) |
|-----------------------|------------|--|--|
| Egg | Lactin-2 | 33.00 | 41.98 |
| Larvae | Lactin-2 | 34.50 | 35.38 |
| Pre-pupa | Polynomial | 29.00 | - |
| Pupa | Polynomial | 32.50 | - |
| Total immature stages | Briere-2 | 34.00 | 35.00 |

Table 6. Lower temperature threshold, optimal temperature and upper temperature threshold of different life stages of *Helicoverpa armigera* obtained by nonlinear models.

8. Strategies for integrated management of *H. armigera*

8.1. Chemical control

Historically pest management on many crops has relied largely on synthetic pesticides and in intensive cropping systems, pesticides are main components of pest management programmes that represents a significant part of production costs [84]. However, chemical control is still the most reliable and economic way of protecting crops from pests. Beside, over reliance on chemical pesticides without regarding to complexities of the agroecosystem is not sustainable and has resulted in many problems like environment pollution, secondary pest outbreak, pest resurgence, pest resistance to pesticides and hazardous to human health. Furthermore, over dependence on chemical pesticides has also resulted in increased plant protection, thus leading to high cost of production.

Insecticide treatments, whether or not included in IPM programmes, are currently indispensable for the control of *H. armigera* in almost all cropping systems around the world [85], so, this pest species has been subjected to heavy selection pressure. Some of the synthetic insecticides currently used for controlling this pest are indoxacarb, methoxyfenozide, emamectin benzoate, novaluron, chlorfenapyr, imidacloprid, fluvalinate, endosulfan, spinosad, abamectin, deltamethrin, cypermethrin, lambda-cyhalothrin, carbaryl, methomyl, profenofos, thiodicarb and chlorpyrifos [21, 85-87]. Because of indiscriminate use of these chemicals to minimize the damage caused by *H. armigera*, however, it has developed high levels of resistance to conventional insecticides such as synthetic pyrethroids, organophosphates and carbamates [88].

8.1.1. Sustainable use of insecticides and obtaining maximum benefits from their application

However, selection for resistance to pesticides will occur whenever they are used [87]. After a pest species develops resistance to a particular pesticide, how do you control it? One method is to use a different pesticide, especially one in a different chemical class or family of pesticides that has a different mode of action against the pest. Of course, the ability to use other pesticides in order to avoid or delay the development of resistance in pest populations depends on the availability of an adequate supply of pesticides with differing modes of action. This method is perhaps not the best solution, but it allows a pest to be controlled until other management strategies can be developed and brought to bear against the pest [21]. However, suggestions will now be made as to how the maximum benefit can be obtained from the unique properties of the insecticides.

- a. Given the decreasing susceptibility of older caterpillars than early ones, it is important to use the insecticides early. Not only young larvae of *H. armigera* are more susceptible, but first and second instars are also more exposed than later instars [89].
- b. To decide whether the infestation by a pest has reached the economic threshold and an insecticide is required, more attention should be devoted to monitoring programmes. On crops where *Helicoverpa* is the main target, synthetic insecticides should not be used until these pests have reached the economic threshold [90].
- c. It is best to be used selective insecticides, a practice that will help to conserve beneficial insects. They can assist in delaying the onset and reducing the intensity of mid-season *Helicoverpa* attack [91].
- d. If infestation is high and the growth of the plants rapid, spray applications should be made at short intervals to protect the new growth, which may from otherwise be attacked by larvae repelled treated older foliage. Furthermore, short interval strategy will give better spray distribution and increase the chance of obtaining direct spray impingement on adults, larvae, and eggs [90].
- e. For crops in which higher economic thresholds are acceptable, integration of synthetic insecticide and beneficial insects becomes a practical possibility. The integration of chemical and biological control is often critical to the success of an IPM programme for arthropod pests [92, 93]. To combine the use of natural enemies with insecticides application, the chemical residues must be minimally toxic to the natural enemies to prevent its population being killed and the target pests increasing again [94]. Toxicological studies that only evaluate the lethal effects may underestimate the negative effects of insecticides on natural enemies and hence, sublethal effects should be assessed to estimate the total effect of insecticides on biological performance of natural enemies [95]. However, even though several studies showed that sublethal effects of insecticides can affect efficiency of natural enemies [96, 97], such effects on these organisms are rarely taken into account when IPM programmes are established and only mortality tests are considered when a choice between several insecticides must be made. Accordingly, to achieve maximum benefit from insecticides application and to reduce the selective pressure and de-

velopment of insecticide resistance, insecticide at low concentrations may be used in combination with biological control.

8.2. Biological control

The most interesting component of IPM for many people is biological control. It is also the most complicated as there is a diverse range of species and types of predators, parasitoids and pathogens. The value of biological control agents in integrated pest management is becoming more apparent as researches are conducted. Natural enemies clearly play an important role in integrated management of *Helicoverpa* spp., particularly in low value crops where they may remove the need for any chemical intervention. Likewise in high value crops (such as cotton and tomato) beneficial species provide considerable benefit but are unable to provide adequate control alone, especially in situations where migratory influxes of *Helicoverpa* result in significant infestations [14]. However, although parasitoids and predators cannot be relied upon for complete control of *H. armigera* in unsprayed area, knowledge about their role in cropping systems where *H. armigera* is an important pest is an essential component in the development of integrated management.

Before using a natural enemy in a biological control programme, it is essential to know about its efficiency. However, study of demographic parameters and foraging behaviors of natural enemies is the reliable criteria for assessment of their efficiency. Among the demographic parameters, intrinsic rate of increase (r_m) is a key parameter in the prediction of population growth potential and has been widely used to evaluate efficiency of natural enemies [22, 76, 98, 99]. In addition to demographic parameters, another important aspect for assessing the efficiency of natural enemies is the study of their foraging behaviors including functional, numerical and aggregation responses, mutual interference, preference and switching [100-110]. Such information is essential to interpret how the natural enemies live, how they influence the population dynamics of their hosts/preys, and how they influence the structure of the insect communities in which they exist [111].

8.2.1. Parasitoids

The most common parasitoids that contribute to mortality of *Helicoverpa* spp. are shown in Table 7. Studies on the effects of parasitoids in biological control of *H. armigera* focused on monitoring parasitism of eggs and larvae. In Botswana, parasitism of larvae collected from different crops averaged up to 50% on sorghum, 28% on sunflower, 49% on cowpeas and 76% on cotton [112]. These results showed that parasitoids had a crucial role in management of *H. armigera*. However, this level of parasitism is higher when compared to the results from East Africa where the level of parasitism was generally low (<5%) or absent [113]. Surveys made of the parasitoid of *Helicoverpa* spp. in cotton fields of Texas by Shepard and Sterling [114] showed that larval parasitoids accounted for approximately 7% regulation of *Helicoverpa* spp. Such investigations highlight importance of parasitoids in integrated management of *H. armigera* in different cropping systems around the world.

| Order | Family | Parasitoid species | References | |
|--------------------------------------|-------------------------------------|---|--------------------------------------|-------|
| Hymenoptera | Trichogrammatidae | <i>Trichogramma pretiosum</i> Riley | [115] | |
| | | <i>Trichogramma exiguum</i> Pinto and Platner | [114] | |
| | | <i>Trichogramma australicum</i> Girault | [116] | |
| | | <i>Trichogramma pretiosum</i> Riley | [117] | |
| | Braconidae | <i>Microplitis croceipes</i> (Cresson) | [115] | |
| | | <i>Habrobracon brevicornis</i> Wesm. | [118] | |
| | | <i>Habrobracon hebetor</i> Say | [17] | |
| | | <i>Cardiochiles nigriceps</i> Vierick | [114] | |
| | | <i>Chelonus insularis</i> Cresson | [119] | |
| | | <i>Apanteles marginiventris</i> (Cresson) | [114] | |
| | | <i>Meteorus</i> sp. | [120] | |
| | | <i>Apanteles ruficrus</i> Hal. | [120] | |
| | | <i>Apanteles kazak</i> Telenga | [121] | |
| | | <i>Microplitis demolitor</i> Wilkinson | [120] | |
| | | <i>Microplitis rufiventris</i> Kok., | [118] | |
| | | <i>Chelonus inanitus</i> (L.), | [118] | |
| | | <i>Chelonus versalis</i> Wilkn | [112] | |
| | | Ichneumonidae | <i>Campoletis sonorensis</i> Cameron | [123] |
| | | | <i>Netelia</i> sp. | [120] |
| | <i>Hyposoter didymator</i> (Thunb.) | | [123] | |
| <i>Heteropelma scaposum</i> (Morley) | [120] | | | |
| <i>Barylypa humeralis</i> Brauns | [118] | | | |
| <i>Campoletis chlorideae</i> Uchida | [124, 125] | | | |
| <i>Pristomerus</i> spp. | [112] | | | |
| <i>Charops</i> spp. | [112] | | | |
| Scelionidae | <i>Telonomus</i> spp. | [112] | | |
| Diptera | Tachinidae | <i>Archytas marmoratus</i> (Townsend) | [114] | |
| | | <i>Eucelatoria bryani</i> Sabrosky | [114] | |
| | | <i>Lespesia archippivora</i> (Riley) | [126] | |
| | | <i>Winthemia</i> sp. | [120] | |
| | | <i>Chaetophthalmus dorsalis</i> (Malloch) | [127] | |
| | | <i>Palexorista laxa</i> (Curran) | [124] | |
| | | <i>Exorista fallax</i> Mg., | [124] | |
| | | <i>Goriophthalmus halli</i> Mesnil | [124] | |
| | | <i>Palexorista</i> sp. | [112] | |
| | | <i>Paradrino halli</i> Curran | [112] | |

Table 7. The most common parasitoids of *Helicoverpa* spp.

8.2.2. Predators

The most important predators of *Helicoverpa* spp. are listed in Table 8. In some cropping systems these predators have considerable impact on population of *Helicoverpa* spp. These biological control agents have been reported as major factors in mortalities of *H. armigera* in cotton agroecosystems in South Africa and in smallholder crops in Kenya. In South Africa the average daily predation rates of 37% and 30% of *H. armigera* eggs and larvae, respectively were found in absence of insecticides [128]. Regarding this considerable potential, some of these predators could be candidates for implementation of biological control programmes. Accordingly, the species of *Sycanus indagator* (Stal) was imported from India to the USA. In another programme, *Pristhesancus papuensis* Stal was introduced from Australia to the USA and its efficiency was evaluated in laboratory [120].

| Order | Family | Predator species | References |
|-------------|---------------------------------|---|------------|
| Coleoptera | Coccinellidae | <i>Scymnus moreletti</i> Sic | [118] |
| | | <i>Exochomus flavipes</i> (Thunberg) | [128] |
| | | <i>Cheilomenes propinqua</i> (Mulsant) | [128] |
| | | <i>Hippodamia varigata</i> Goeze | [128] |
| | | <i>Coccinella</i> sp. | [118] |
| | Carabidae | <i>Calosoma</i> spp. | [129] |
| | Staphilinidae | - | [128] |
| Hymenoptera | Formicidae | <i>Pheidole</i> spp. | [128] |
| | | <i>Myrmecaria</i> spp. | [128] |
| | | <i>Dorylus</i> spp. | [128] |
| Hemiptera | Miridae | <i>Campylomma</i> sp. | [128] |
| | Anthocoridae | <i>Orius thripoborus</i> (Hesse) | [113] |
| | | <i>Cardiastethus exiguous</i> (Poppius) | [113] |
| | | <i>Orius albidipennis</i> (Reuter), | [113] |
| | | <i>Orius tantillus</i> (Motschulsky) | [113] |
| | | <i>Blaptostethus</i> sp. | [113] |
| | | <i>Cardiastethus</i> sp. | [113] |
| | Reduviidae | <i>Sycanus indagator</i> (Stal) | [130] |
| | Reduviidae | <i>Pristhesancus papuensis</i> Stal | [120] |
| | Pentatomidae | <i>Podisus maculiventris</i> (Say) | [131] |
| Nabidae | <i>Nabis</i> spp. | [129] | |
| Lygaeidae | <i>Geocoris punctipes</i> (Say) | [131] | |
| Neuroptera | Chrysopidae | <i>Chrysoperla carnea</i> (Stephens) | [132] |

Table 8. Important predators of *Helicoverpa* spp.

8.2.3. Pathogens

Naturally occurring entomopathogens are important regulatory factors in insect populations. The application of microorganisms for control of insect pests was proposed by notable early pioneers in invertebrate pathology such as Agostino Bassi, Louis Pasteur and Elie Metchnikoff [133]. However, it was not until the development of the bacterium *Bacillus thuringiensis* Berliner (*Bt*) that the use of microbes for the control of insects became widespread. Today a variety of entomopathogens (bacteria, viruses, fungi, protozoa, and nematodes) are used for the control of insect pests [134]. However, when environmental benefits of these pathogens including safety for humans and other nontarget organisms, reduction of pesticide residues in food and environment, increased activity of most other natural enemies and increased biodiversity in managed ecosystems are taken into account, their advantages are numerous. There are also some disadvantages, mostly linked with their persistence, speed of kill, specificity (too broad or too narrow host range) and cost relative to conventional chemical insecticides. However, their increased utilization will require (a) increased pathogen virulence and speed of kill; (b) improved pathogen performance under challenging environmental conditions; (c) greater efficiency in their production; (d) improvements in formulation that enable ease of application, increased environmental persistence, and longer shelf life; (e) better understanding of how they will fit into integrated systems and their interaction with the environment and other IPM components and (f) acceptance by growers and the general public [134].

The critical need for safe and effective alternatives to chemical insecticides in integrated management of *H. armigera* has stimulated considerable interest in using pathogens as biological control agents. A list of some isolated microorganisms from *Helicoverpa* spp. is presented in Table 9. Among these microorganisms, nuclear polyhedrosis virus (NPV) and *B. thuringiensis* have a considerable effect on population of *H. armigera*. Potential of these pathogens in management programmes of *H. armigera* were evaluated by several researchers. Roome [135] tested a commercial preparation of NPV against *H. armigera*. The results showed that NPV was as effective as a standard insecticide in reducing yield loss on sorghum due to damage by *H. armigera*. In addition, the long survival of NPV on sorghum (80 days) indicated that a single application of NPV was adequate to protect the crop for a growing season. In another study, Moore *et al.* [136] showed that NPV has potential in management of *H. armigera* on citrus trees. Recent work by Jeyarani *et al.* [137] revealed that NPV has an acceptable efficiency in control of *H. armigera* on cotton and chickpea.

Pathogenicity of *B. thuringiensis* for management of *H. armigera* population was investigated by several researchers [19, 144]. They showed that larvae ingest enough quantities of *B. thuringiensis* toxins to die, or at least to reduce its weight and development, depending on the toxin and conditions of the experiment. In a recent study, sublethal effects of *B. thuringiensis* on biological performance of *H. armigera* were investigated [Sedaratian and Fathipour, unpublished data]. According to results obtained, values recorded for duration of total immature stages increased from 31.87 days in control to 37.17 days in LC₂₅. Furthermore, female longevity decreased from 13.14 days to 7.23 days. Fecundity was also negatively affected in female moths developed from treated neonates, with the rate of egg hatchability reaching

zero. The results obtained also revealed that the sublethal effects of *B. thuringiensis* could carry over to the next generation. The intrinsic and finite rates of increase (r_m and λ , respectively) were significantly lower in insects treated with sublethal concentrations compared to control. Consequent with the reduce rate of development observed for *H. armigera* treated with *B. thuringiensis*, the doubling time (DT) were significantly higher in insects exposed to any concentration tested compared to control (Table 10). However, according to results obtained, *B. thuringiensis* could play a critical role in integrated management of *H. armigera*.

| Group | Family | Pathogen species | References |
|----------|--------------------|---|------------|
| Bacteria | Enterobacteriaceae | <i>Pantoea agglomerans</i> (Ewing and Fife) | [138] |
| | Bacillaceae | <i>Bacillus thuringiensis</i> Berliner | [19] |
| Fungi | Cordycipitaceae | <i>Beauveria bassiana</i> (Balsamo) | [139] |
| | Clavicipitaceae | <i>Metarhizium anisopliae</i> (Metsch.) | [140] |
| | Moniliaceae | <i>Nomuraea rileyi</i> (Farlow) Samson | [141] |
| Viruses | Baculoviridae | Nuclear Polyhedrosis Virus | [142] |
| Nematoda | Heterorhabditidae | <i>Heterorhabditis bacteriophora</i> Poinar | [143] |
| | Steinernematidae | <i>Steinernema carpocapsae</i> (Weiser) | [143] |
| | | <i>Steinernema feltiae</i> (Filipjev) | [143] |

Table 9. Some of the isolated microorganisms from *Helicoverpa* spp.

| Generation Parameter | | Treatments | | | | | |
|----------------------|--------------------------------|-------------------|-------------------|-------------------|-------------------|-------------------|------------------|
| | | Control | LC ₅ | LC ₁₀ | LC ₁₅ | LC ₂₀ | LC ₂₅ |
| Parental | Total immature stages | 31.87±0.38 c | 34.81±0.24 b | 35.63±0.52 b | 34.74±0.31 b | 36.17±0.42 ab | 37.17±0.43 a |
| | Female longevity | 13.14±0.40 a | 11.69±0.48 ab | 10.28±0.86 bc | 10.06±0.67 bc | 9.27±0.44 c | 7.23±0.44 d |
| | Total fecundity | 789.52±42.68 a | 665.13±52.46 b | 601.00±45.72 b | 532.53±33.70 b | 376.00±21.95 c | 98.46±12.33 d |
| Offspring | r_m (day ⁻¹) | 0.19±0.00 a | 0.18±0.00 a | 0.16±0.00 b | 0.14±0.00 c | 0.13±0.00 d | -* |
| | λ (day ⁻¹) | 1.21±0.00 a | 1.20±0.00 a | 1.1±0.00 b | 1.16±0.01 c | 1.14±0.00 d | - |
| | DT (day) | 3.59±0.05 d | 3.75±0.05 d | 4.29±0.08 c | 4.78±0.08 b | 5.33±0.16 a | - |

Means in a row followed by the same letters are not significantly different (P < 0.05) (S.N.K.)

* In this treatment hatch rate reaching zero.

Table 10. Sublethal effects of *Bacillus thuringiensis* on biological performance of *Helicoverpa armigera* in two subsequent generations.

The reliance on the entomopathogens for management of *H. armigera*, however, is risky since the different factors that govern epizootics. Accordingly, in most cases no single microbial control agent will provide sustainable control of this pest. Nevertheless, as components of an integrated management programme, entomopathogens can provide significant and selective control [134]. In the not too distant future we envision a broader appreciation for the attributes of entomopathogens and expect to see synergistic combinations of microbial control agents with other technologies that will enhance the effectiveness and sustainability of integrated management of *H. armigera*.

8.3. Cultural control

Cultural control is the deliberate manipulation of the cropping or soil system environment to make it less favorable for pests or making it more favorable for their natural enemies. Many procedures such as tillage, host plant resistance, planting, irrigation, fertilizer applications, destruction of crop residues, use of trap crops, crop rotation, etc. can be employed to achieve cultural control. Early workers used cultural practices as the mainstay of their insect control efforts. Newsom [145] pointed out that the rediscovery of the importance of cultural control tactics has provided highly effective components of pest management systems. Although some cultural practices have a noticeable potential in integrated management, use of some cultural controls is not universally beneficial. For example, providing nectar sources for beneficial insects may also provide nectar sources for pests.

8.3.1. Uncultivated marginal areas and abundance of natural enemies

Monoculture in modern agriculture, especially in annual crops, often discriminates against natural enemies and favors development of explosive pest populations. According to Fye [146], management of naturally occurring populations of insect predators may depend on knowledge of the succession of winter weeds and crops that provide natural hosts for food and shelter. The results obtained by Whitcomb and Bell [147] revealed that very few predators move directly from overwintering sites to field and pass one or two generations on weeds in the uncultivated marginal areas. In a 2-year study on the abundance of predators of *Helicoverpa* spp. in the various habitats in the Delta of Mississippi, predator populations in all the marginal areas were observed to be much higher than in the more homogeneous areas such as soybean fields.

8.3.2. Intercropping and its effect on natural enemies

Dispersal from target area often reduces the effectiveness of natural enemies especially in augmentation programmes. To minimize this shortcoming, provision of supplemental resources such as food to maintain, arrest or stimulate the released natural enemy could provide mechanisms for managing parasitoids and predators [148]. Accordingly, some environmental manipulation could affect efficiency of a natural enemy during biological control programmes of *Helicoverpa* spp. Roome [149] suggested that increasing plant diversity in cropping systems by intercropping crops carrying nectars could enhance effectiveness of natural enemies. When different host plants of *H. armigera* are interplanted, population of

H. armigera and its natural enemies on a crop are influenced by neighboring crops, both directly and indirectly. Direct influences include preference for one crop over the other by ovipositing moths and the movement of larvae and natural enemies between interplanted crops. Indirect influences arise when *H. armigera* infestation on one crop is influenced by the population build-up or mortality level on neighboring crops [113].

8.3.3. Ploughing and early planting effects on *Helicoverpa* populations

An alternative and often complementary strategy for management of *H. armigera* is the control of overwintering pupae through the practice of pupae busting which has been used in several cropping areas. Ploughing in late maturing crops in winter increase the mortality of any pupae formed in cropland by exposing them to heat and predation. The other cultural control method is early planting which avoids the seasonal peaks of population thereby avoiding very heavy larval infestations and reducing the overwintering population [150].

8.3.4. Trap crops and management of *H. armigera*

The recent resurgence of interest in trap cropping as an IPM tool is the result of concerns about potential negative effects of pesticides. Prior to the introduction of modern synthetic insecticides, trap cropping was a common method of pest control for several cropping systems [150]. Trap crops have been defined as “plant stands that are, per se or via manipulation, deployed to attract, divert, intercept and retain targeted insects or the pathogens they vector in order to reduce damage to the main crop” [151, 152]. Trap cropping is essentially a method of concentrating a pest population into a manageable area by providing the pest with an area of a preferred host crop and when strategically planned and managed, can be utilized at different times throughout the year to help manage a range of pests. For example, spring trap crops are designed to attract *H. armigera* as they emerge from overwintering pupae. A trap crop, strategically timed to flower in the spring, can help to reduce the early season buildup of *H. armigera* in a district. Spring trap cropping, in conjunction with good *Helicoverpa* control in crops and pupae busting in autumn, is designed to reduce the size of the local *Helicoverpa* population. On the other hand, summer trap cropping has quite a different aim from that of spring trap cropping. A summer trap crop aims to draw *Helicoverpa* away from a main crop and concentrate them in another crop. Once concentrated into the trap crop, the *Helicoverpa* larvae can be controlled. Finally, in addition to diverting insect pests away from the main crop, trap crops can also reduce insect pest populations by enhancing populations of natural enemies within the field. For example, a sorghum trap crop used to manage *H. armigera*, also increases rates of parasitism by *Trichogramma chilonis* Ishii [153]. However, to avoid creating a nursery for *H. armigera*, the trap crop must be destroyed prior to the pupation of the first large *H. armigera* larvae. Furthermore, to protect the trap crop from large infestations of *Helicoverpa* spp. spraying may be required.

8.3.4.1. Trap crops and push-pull strategy in integrated management of *H. armigera*

The term push-pull was first applied as a strategy for IPM by Pyke *et al.* in Australia in 1987 [154]. They investigated the use of repellent and attractive stimuli, to manipulate

the distribution of *Helicoverpa* spp. in cotton fields. Push-pull strategies involve the “behavioral manipulation of insect pests and their natural enemies via the integration of stimuli that act to make the protected resource unattractive or unsuitable to the pests (push) while luring them toward an attractive source (pull) from where the pests are subsequently removed”. The strategy is a useful tool for integrated pest management programmes reducing pesticide input [155].

In plant-based systems, naturally generated plant stimuli can be exploited using vegetation diversification, including trap cropping and these crops have a crucial role as one of the most important stimuli for pull components. The host plant stimuli responsible for making a particular plant growth stage, cultivar, or species naturally more attractive to pests than the plants to be protected can be delivered as pull components by trap crops [155]. However, the relative attractiveness of the trap crop compared with the main crop, the ratio of the main crop given to the trap crop, its spatial arrangement (i.e., planted as a perimeter or intercropped trap crop), and the colonization habits of the pest are crucial to success and require a thorough understanding of the behavior of the pest [156].

In the case of *Helicoverpa* spp. on cotton in Australia, the potential of combining the application of neem seed extracts to the main crop (push) with an attractive trap crop, either pigeonpea or maize (pull), to protect cotton crops from *H. armigera* and *H. punctigera* has been investigated [153]. Trap crops, particularly pigeonpea, reduced the number of eggs on cotton plants in target areas. In trials, the push-pull strategy was significantly more effective than the individual components alone. The potential of this strategy was supported by a recent study in India. Neem, combined with a pigeonpea or okra trap crop, was an effective strategy against *H. armigera* [157].

8.3.5. Host plant resistance

Plants that are inherently less damaged or infested by insect pests in comparable environments are considered resistant [158]. Host plant resistance (HPR) is recognized as the most effective component of IPM and has been considered to replace broad spectrum insecticides. A resistant host plant provides the basic foundation on which structures of IPM for different pests can be built [159]. The advantage that farmers gain in using cultural control with susceptible cultivars would certainly be enhanced when combined with the resistant cultivars. Adkisson and Dyck [160] stated that resistant cultivars are highly desirable in a cultural control systems designed to maintain pest numbers below the economic injury level (EIL) while preserving the natural enemies. Besides, even low level of resistance is important because of reduction of the need for other control measures in the crop production systems. Furthermore, with low value crops, where chemical control is not economical, the use of HPR may be the only economic solution to a pest problem [46]. However, the most advantageous features of HPR are the following: (a) cheapest technology; (b) easiest to introduce; (c) is specific to one or several pests; (d) cumulative effectiveness makes high level of resistance unnecessary; (e) is persistence; (f) can easily be adopted into normal farm operations; (g) is compatible with other control tactics in IPM such as chemical, biological and cultural control; (h) reducing the costs to the growers and (I) it is not detrimental to the environment [160, 161].

Generally, the phenomena of resistance are based on heritable traits. However, some traits fluctuate widely in different environmental conditions. Accordingly, plant resistance may be classified as genetic, implying the traits that are under the primary control of genetic factors; or ecological, implying the traits that are under the primary control of environmental factors. Host plants with genetic resistance to insect pest are very pleasure in IPM programmes [159]. This type of resistance is subdivided into two categories including induced and constitutive resistance. If biotic and abiotic environmental factors reduces insect fitness or negatively affects host selection processes, the effect is called induced resistance. On the other hand, constitutive resistance involves inherited characters whose expression, although influenced by the environment, is not triggered by environmental factors [41]. However, genetic resistance to insect pest could be results of three distinct mechanisms including antixenosis, antibiosis and tolerance. Antixenosis is the resistance mechanism employed by plant to deter or reduce colonization by insect. Antibiosis is the resistance mechanism that operates after the insect have colonized and started utilizing the plant. This mechanism could affect growth, development, reproduction and survivorship of insect pests and therefore, is the most important mechanism for IPM purposes. Tolerance is a characteristic of some plants that enable them to withstand or recover from insect damage [159].

Plant resistance to insect pests can be inherited in two distinct ways including vertical (monogenic) and horizontal (polygenic) resistance. Vertical resistance is generally controlled by a single gene, referred as R-gene. These R-genes can be remarkably effective in suppression of pest populations and can confer complete resistance. However, each R-gene confers resistance to only one insect pest and thus, depending on the pest species in specific area a cultivar may appear strongly resistant or completely susceptible. Horizontal resistance is also known as polygenic resistance due to this type of resistance is controlled by many genes. Unlike vertical resistance, horizontal resistance generally does not completely prevent a plant from becoming damaged. For insect pests, this type of resistance may slow the infection process so much that the pest does not grow well or spread to other plants. However, because of the large number of genes involved, it is much more difficult to breed cultivars with horizontal resistance to insect pests [162].

8.3.5.1. Plant resistance to *H. armigera*

To evaluate plant resistance to *H. armigera* several researchers evaluate population growth parameters of this pest on different host plants. Table 11 presents the main finding of several studies regarding to population growth parameters of this noctuid pest on different crop plants. However, information about population growth parameters of *H. armigera* on different host plants could reveal the suitability of one crop for this noctuid pest than other host plants.

In the case of *H. armigera* on different soybean cultivars, resistance of some cultivars to this noctuid pest was evaluated under laboratory conditions [6]. Results obtained by these researchers showed that various soybean cultivars differed greatly in suitability as diets for *H. armigera* when measured in terms of development, survivorship, life table parameters and nutritional indices. Fathipour and Naseri [11] presented detailed information regarding

evaluation of soybean resistance to *H. armigera* in a book chapter entitled “ Soybean cultivars affecting performance of *Helicoverpa armigera* (Lepidoptera: Noctuidae) ”. This chapter is now freely available on the INTECH website at <http://www.intechopen.com/articles/show/title/soybean-cultivars-affecting-performance-of-helicoverpa-armigera-lepidoptera-noctuidae->. However, a review of literature showed that a little information regarding resistance evaluation in field conditions is available and hence, for sustainable management of *H. armigera* in soybean cropping systems more attention should be devoted to fill this gap.

| Crop | Experimental conditions | | R_o (female offspring) | r_m (day ⁻¹) | T (day) | DT (day) | References |
|--------------------------|-------------------------|-------------------------|--------------------------|----------------------------|---------------|--------------|------------|
| | Temperature °C | Diet type | | | | | |
| Canola (10) ^a | 25 | artificial ^b | 157.4 - 331.5 | 0.153 - 0.179 | 31.10 - 36.10 | 3.80 - 4.50 | [12] |
| Chickpea | 25 | artificial | 359.67 | 0.161 | 33.28 | 4.27 | [c] |
| Chickpea (4) | 25 | artificial | 59.49 - 195.00 | 0.140 - 0.205 | 24.11 - 30.36 | 3.40 - 4.88 | [d] |
| Common bean | 27 | leaf and fruit | 19.50 | - | - | - | [163] |
| Corn | 25 | artificial | 203.14 | 0.130 | 40.56 | 5.29 | [84] |
| Corn | 25 | artificial | 147.40 | 0.126 | 37.90 | 5.62 | [c] |
| Corn | 27 | leaf and fruit | 44.50 | - | - | - | [163] |
| Corn | | cob | 50.1 | 0.0853 | 46.6 | - | [164] |
| Cotton | 27 | leaf and fruit | 117.60 | - | - | - | [163] |
| Cowpea | 25 | artificial | 228.5 | 0.131 | 34.88 | 5.28 | [e] |
| Cowpea | 25 | artificial | 365.66 | 0.180 | 31.62 | 3.92 | [c] |
| Cowpea | 25 | artificial | 250.60 | 0.178 | 30.38 | 3.85 | [d] |
| Hot pepper | 27 | leaf and fruit | 5.10 | - | - | - | [163] |
| Navy bean | 25 | artificial | 294.28 | 0.164 | 32.31 | 4.14 | [c] |
| Pearl millet | - | - | 374.01 | 0.142 | - | - | [165] |
| Soybean | 25 | artificial | 239.69 | 0.161 | 33.28 | 4.23 | [c] |
| Soybean (10) | 25 | artificial | 16.00 - 270.00 | 0.084 - 0.114 | 36.72 - 45.28 | 6.08 - 8.10 | [6] |
| Soybean (13) | 25 | leaf and pod | 89.35 - 354.92 | 0.132 - 0.185 | 28.85 - 36.61 | 3.75 - 5.23 | [166] |
| Sunflower | - | - | 143.77 | 0.113 | - | 6.11 | [167] |
| Tobacco | 27 | leaf | 11.70 | - | - | - | [163] |
| Tomato | 27 | leaf and fruit | 9.5 | - | - | - | [163] |
| Tomato (10) | 25 | leaf and fruit | 1.36 - 62.32 | 0.008 - 0.137 | 30.26 - 37.34 | 5.06 - 27.41 | [f] |

^a Digits in parentheses show number of tested cultivars.

^b Artificial diet based on the seed of host plant.

[c] Baghery and Fathipour, unpublished data; [d] Fallahnejad-Mojarrad and Fathipour, unpublished data; [e] Adigozali and Fathipour, unpublished data; [f] Safuraie and Fathipour, unpublished data.

Table 11. Effects of different host plants on some population growth parameters of *Helicoverpa armigera*

8.3.5.2. Integration of HPR with other control measures and possible interactions

Several studies have been performed to investigate the possible interactions of host plant resistance to insect with other control measures. Results obtained revealed both incompatibility and compatibility of HPR in an integrated programme. However, in IPM programmes there can be three types of interactions between different control measures including additive, synergistic, and antagonistic. Additive interaction means the combined effect of two control measures is equal to the sum of the effect of the two measures taken separately. In synergistic interaction, the effect of two control measures taken together is greater than the sum of their separate effect. Finally, antagonistic interaction means that the effect of two control measures is actually less than the sum of their effects taken independently of each other. However, despite importance of such information in IPM, a little knowledge in this field is available.

8.3.5.2.1. HPR and biological control

Plant resistance and biological control are the key components of IPM for field crops and generally considered to be compatible. Insects feeding on HPR commonly experience retarded growth and an extended developmental period. Under field conditions, such poorly developed insect herbivores are more vulnerable to natural enemies for a longer period and the probability of their mortality is higher. Insect herbivores that develop slowly on resistant cultivars are more effectively regulated by the predators than those developed robustly on the susceptible cultivars. This is because the predator has to consume more small-sized prey to become satiated [168]. Wiseman *et al.* [169] found that populations of *Orius insidiosus* (Say), a predator on *H. zea* larvae, were higher on the resistant corn hybrids than on the susceptible ones, an indication of the compatibility of HPR and the predator.

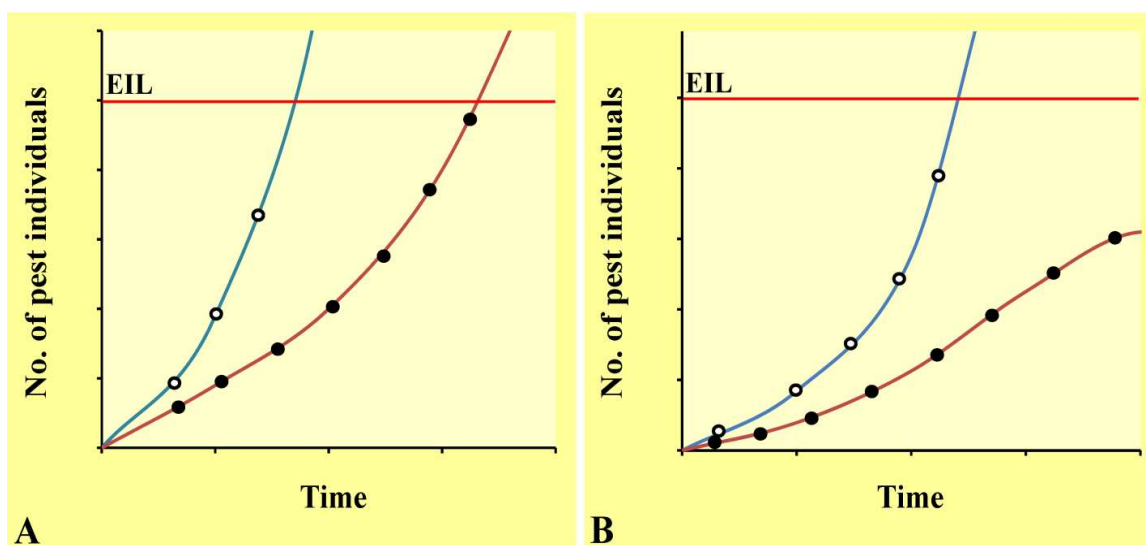


Figure 4. Influence of a low level of plant resistance to pest attack on the effectiveness of natural enemies. ○, without predator; ●, with predator. Predator activity fails to exert economic control of insect pests on susceptible plants (A), whereas the same degree of predator activity exert economic control of the insect pest on plants with some degree of resistance (B) (after van Emden and Wearing [170]).

van Emden and Wearing [170] developed a simple model on the interaction of HPR with natural enemies. On the basis of this model, the reduced rate of multiplication of aphids on moderator resistant cultivars should magnify the plant resistance in the presence of natural enemies (Figure 4). Danks *et al.* [123] stated that a number of predators and parasitoids attack early instars of *Helicoverpa* sp. on soybean and tobacco but generally do not attack bigger larvae. But because of moderately resistance of host plants, the larvae remain in early instars for longer period and are more likely to be parasitized. However, such interactions are valuable phenomenon in the development of practical IPM.

However, there are instances of deleterious interactions between HPR and biological control which could be more important in the IPM. Sometimes, plant morphological traits and plant defense chemicals had adverse effects on the natural enemies. For example, certain genotypes of tobacco with glandular trichomes have been shown to severely limit the parasitization of the eggs of *Manduca sexta* (Linnaeus) by *Trichogramma minutum* Riley [171]. Resistant eggplant cultivars to *Tetranychus urticae* Koch adversely affected biological performance of *Typhlodromus bagdasarjani* Wainstein and Arutunjan [22]. These researchers stated that antibiotic compounds in resistant cultivars are also toxic for *T. bagdasarjani* and concentrated compounds in the *T. urticae* reduced effectiveness of this predator. Barbour *et al.* [172] found that methylketone adversely affected the egg predators of *H. zea* that fed on the foliage of wild tomato. However, plant breeders can sometimes manipulate plant traits to promote the effectiveness of natural enemies [159]. For example, a reduction in trichomes density of cucumber leaves significantly increase effectiveness of *Encarsia formosa* Gahan on the greenhouse whitefly [173].

8.3.5.2.2. HPR and insect pathogens

Schultz [174] hypothesized that the effectiveness of insect pathogens may be reduced or improved, depending upon plant chemistry and variability of plant resistance. Interactions among HPR, herbivores and their pathogens can alter pathogenicity of *B. thuringiensis* on *M. sexta* [175]. Furthermore, insect susceptibility to the entomopathogenic fungus can also be affected by HPR. Felton and Duffey [176] reported the possible incompatibility of resistant cultivars of tomato with NPV control of *H. zea*. These researchers revealed that chlorogenic acid in resistant cultivars of tomato is oxidized by foliar phenol oxidases and generated components binds to the occlusion bodies of NPV, thereby decreasing its pathogenicity against *H. zea*.

8.3.5.2.3. HPR and chemical control

There is usually a beneficial interaction between HPR and chemical control. Because the toxicity of an insecticide is a function of insect bodyweight, it is expected that a lower concentration is needed to control insect feeding on a resistant cultivar than those feeding on a susceptible ones [177]. van Emden [178] pointed out that there is a potentially useful interaction in the possibility of using reduced doses of insecticide on resistant cultivar, when spray is needed. This theory relies on the selectivity of the insecticide in favor of natural enemies as dose rate is reduced (Figure 5). However, it appears that

even in the presence of small levels of plant resistance, insecticide concentration can be reduced to one-third of that required on a susceptible cultivar [178]. This reduced use of pesticide not only benefits the agroecosystems and natural enemies but also results in lower pesticide residues in the human food chain. Accordingly, Wiseman *et al.* [179] showed that even one low-dose application of insecticide to the resistant hybrid of corn gave an *H. zea* control equal to that achieved with seven applications to the susceptible hybrid. Fathipour *et al.* [25] compared the chemical control of *Eurygaster integriceps* Put. on resistant and susceptible cultivars of wheat. The results obtained by these researchers revealed that the sensitivity of 4th and 5th instar nymphs and new adults of *E. integriceps* to insecticide Fenitrothion was enhanced on resistant cultivar compared with those on susceptible cultivar. Accordingly, the LC_{50} of insecticide on susceptible and resistant cultivars for 4th instar nymphs was 42.16 and 33.48, for 5th instar nymphs was 147.03 and 114.01 and for new adults was 303.35 and 227.88 ppm, respectively.

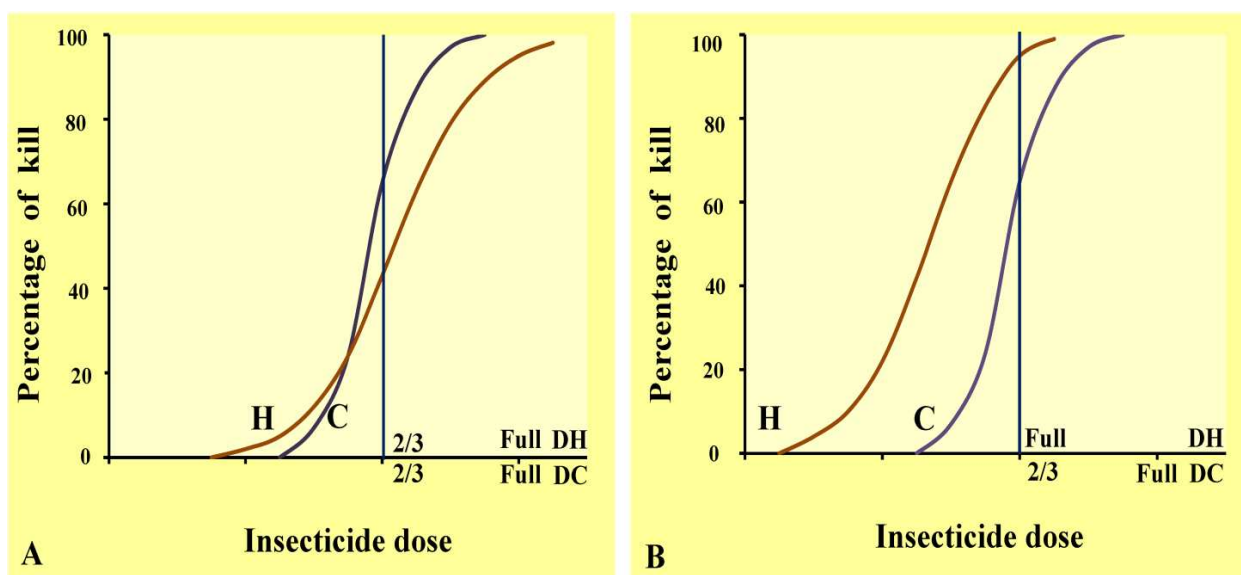


Figure 5. Effect of plant resistance on the selectivity of an insecticide. A: susceptible cultivar; B: resistant cultivar where dose for the herbivore can be reduced by one third; C: dose mortality curve for carnivore; H: dose mortality curve for herbivore; DC: dose scale for carnivore; DH: dose scale for herbivore (after van Emden, [178]).

However, in addition to negative effects on insect bodyweight, repellent chemicals or morphological traits of resistant cultivars may be effective in reduction of insecticide spray. Repellency is to be effective in limiting pest damage to treated crops and it may also keep the pests away from their suitable resources and therefore cause indirect mortality or lower fecundity. Furthermore, repellency is equivalent to using low doses of insecticides along with the repellent properties of the host plant [159].

8.4. Semiochemicals and their possible use in suppression of *H. armigera* populations

Many insects and other arthropods rely on chemical messages to communicate with each other or to find suitable hosts. Chemical messages that trigger various behavioral responses

are collectively referred to as semiochemicals. Generally, semiochemicals is subdivided into two distinct groups including pheromones and allelochemicals (Table 12). The term pheromone is used to describe compounds that operate intraspecifically, while allelochemical is the general term for an interspecific effector [26]. However, the realization that behaviors critical to insect survival were strongly influenced by semiochemicals rapidly led to proposals for using these agents as practical tools for pest suppression [180].

| | | | |
|----------------|------------------------------|----------------------|--|
| Semiochemicals | Pheromones ^a | Sex ph. | A volatile chemical substance produced by one sex of an insect which produces some specific reaction in the opposite sex. |
| | | Aggregation ph. | Also known as arrestants. These are chemicals that cause insects to aggregate or congregate. |
| | | Alarm ph. | A substance produced by an insect to repel and disperse other insects in the area. |
| | | Trail ph. | A substance laid down in the form of a trail by one insect and followed by another member of the same species. |
| | | Host-marking ph. | A substance placed inside/outside of the host body at the time of oviposition to distinguish unparasitized from parasitized hosts. |
| | | Caste-regulating ph. | A substance used by social insects to control the development of individuals in a colony. |
| | Allelochemicals ^b | Allomone | A substance produced by a living organism that evokes in receiver a behavioral or physiological reaction that is adaptively favorable to the sender. |
| | | Kairomone | A substance produced by a living organism that evokes in receiver a behavioral or physiological reaction that is adaptively favorable to the receiver. |
| | | Synomone | A substance produced by an organism that evokes in the receiver a behavioral or physiological reaction that is adaptively favorable to both sender and receiver. |
| | | Antimone | A substance produced by an organism that evokes in the receiver a behavioral or physiological reaction that activates a repellent response to the sender and is unfavorable to both sender and receiver. |
| | | Apneumone | A substance emitted by a nonliving material that evokes a behavioral or physiological reaction that is adaptively favorable to a receiving organism but detrimental to an organism of another species that may be found in or on the nonliving material. |

^a classified according to function

^b classified according to the advantage to receiver or sender

Table 12. Classification of behavior-modifying chemicals (semiochemicals)

As discussed in previous section (see section 6) and in addition to using the pheromones of *Helicoverpa* spp. for essential monitoring of infested areas, these compounds have been shown to be useful for suppression of *Helicoverpa* infestation. Attractant-baited lures form the basis for three direct control measures: (1) mass trapping of male, (2) attract-and-kill strategy and (3) mating disruption via permeating the atmosphere of crop environments with sex pheromones. Potential of synthesized pheromones for mass trapping of *H. armigera* was investigated by several researchers. According to Pawar *et al.* [181], *H. armigera* will readily respond to synthesized pheromones and traps are capable of capturing hundreds of male moths per trap per night. The same results were reported by Reddy and Manjunath [18]. Attract-and-kill is a promising new strategy that involves an attractant such as a pheromone and a toxicant. Unlike mating disruption, which functions by confusing the insect, this strategy attracts the insect to a pesticide laden gel matrix and kills them. This strategy has been successfully used on several lepidopteran species [18] but no information is available in the case of *Helicoverpa* spp. However, the most developed tactic is mating disruption. This approach entails releasing large amounts of synthetic sex pheromone into the atmosphere of a crop to interfere with mate-finding, thereby controlling the pest by curtailing the reproductive phase of its life cycle. Mating disruption through the use of some synthesized pheromone such as (Z)-9-tetradecen-1-ol for air permeation is a potentially valuable development in integrated management of *Helicoverpa* spp. It has been shown to be very effective with *H. zea* and *H. virescens* and should certainly be pursued for the same purpose with *H. armigera* [182].

9. Biotechnology in IPM

Recent advantage in biotechnology, particularly cellular and molecular biology have opened new avenues for developing resistant cultivars. From this diagnostic perspective, molecular techniques are likely to play an important role in identification, quantification and genetic monitoring of pest populations [183]. The diagnostic information is a necessary prerequisite for implementing rational control strategy. Appropriate molecular techniques can be employed to study the species composition of the pest population and to identify strains, races or biotypes of the same species.

Another important application of molecular diagnostic techniques is for monitoring both the presence and frequency of genes of particular interest. For example, genes for resistance to a specific class of pesticides and their frequency in particular region can be assessed. Such information is very useful for designing and implementing rational pest management strategies [159].

The most important application of biotechnology in IPM is the introduction of novel genes for resistance into crop cultivars through genetic engineering. HPR is a highly effective management option, but cultivated germplasm has only low to moderate resistance levels to some key pests. Furthermore, some sources of resistance have poor agronomic characteristics. On the other hand, development of cultivars with enhanced resistance will strengthen

the control of *H. armigera* in different cropping systems. Therefore, we need to make a concerted effort to transfer pest resistance into genotypes with desirable agronomic and grain characteristics. Recent achievements of genetics and molecular biology have been widely implemented into breeding new crop cultivars and brought in many various traits absent from parent species and cultivars. Furthermore, new progress in biotechnology makes it feasible to transfer genes from totally unrelated organisms, breaking species barriers not possible by conventional genetic enhancement. Today, transgenic plants expressing insecticidal proteins from the bacterium *B. thuringiensis*, are revolutionizing agriculture. *Bacillus thuringiensis* has become a major insecticide because genes that produce *B. thuringiensis* toxins have been engineered into major crops grown on 11.4 million ha worldwide (including soybean, cotton, peanut, tomato, tobacco, corn and canola). These crops have shown positive economic benefits to growers and reduced the use of other insecticides. Genetically engineered cottons expressing delta-endotoxin genes from *B. thuringiensis* offer great potential to dramatically reduce pesticide dependence for control of *Helicoverpa* spp. and consequently offer real opportunities as a component of sustainable and environmentally acceptable IPM systems [16]. Certainly, for sustainable management of *H. armigera* in soybean cropping systems, such soybean resistant cultivars could play pivotal role. Therefore, to achieve this goal, much works should be conducted in breeding new soybean cultivars expressing *Bt* toxins against *H. armigera*.

The potential ecological and human health consequences of *Bt* crops, including effects on nontarget organisms, food safety, and the development of resistant insect populations, are being compared for *Bt* plants and alternative insect management strategies. However, *Bt* plants were deployed with the expectation that the risks would be lower than current or alternative technologies and that the benefits would be greater. Based on the data to date, these expectations seem valid [16]. The major challenge to sustainable use of transgenic *Bt* crops is the risk that target pests may evolve resistance to the *B. thuringiensis* toxins. *Helicoverpa armigera* is a particular resistance risk having consistently developed resistance to synthetic pesticides in the past [21]. For this reason a pre-emptive resistance management strategy was implemented to accompany the commercial release of transgenic cultivars. The strategy, based on the use of structured refuges to maintain susceptible individuals in the population, seeks to take advantage of the polyphagy and local mobility of *H. armigera* to achieve resistance management by utilizing gene flow to counter selection in transgenic crops. However, refuge crops cannot be treated with *Bt* sprays, and must be in close proximity to the transgenic crops (within 2 km) to maximize the chance of random mating among sub-populations [184].

10. Tritrophic interactions and its manipulation for IPM

Plant quality can affect herbivore fitness directly (as food of herbivores) and indirectly (by affecting foraging cues for natural enemies) [12, 23]. Until recently, there has been a tendency by those involved in IPM to be principally concerned with effects on herbivores or interactions between just two trophic levels [185]. However, interest in the importance of

interactions among the three or four trophic levels (Figure 6) that characterize most natural systems and agroecosystems has been increased rapidly during the last two decades [26].

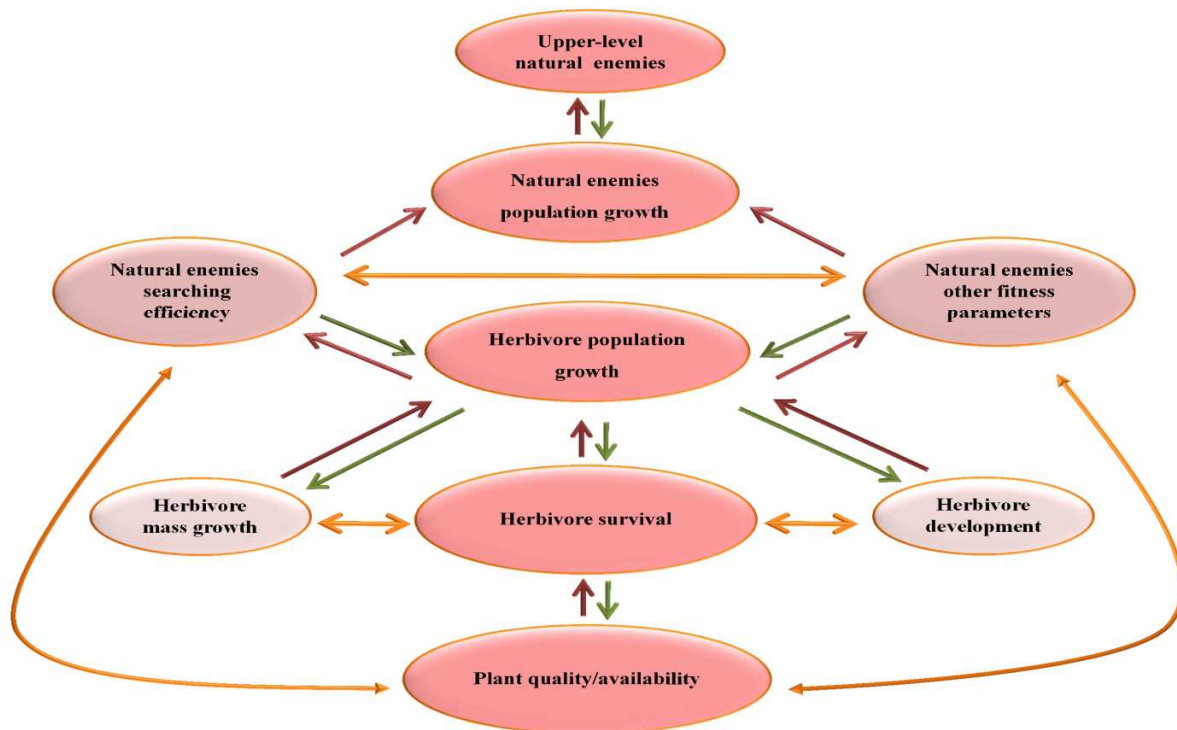


Figure 6. Simple diagram of multitrophic interactions representing some important causal relationships among the trophic levels mediated by some important insect fitness parameters

It is interesting that many traditional cultural practices exert their effects through complex multitrophic interactions, but it is exactly this complexity that makes such systems difficult to assess experimentally or validate conclusively across a broad range of environments. For example, it has been demonstrated that toxic secondary compounds in an herbivore diet may affect development, survivorship, morphology and size of its natural enemies. This effect of poor-quality plants can thus indirectly lead to poor-quality natural enemies [186].

As knowledge of interactions across multitrophic systems both in nature and in agroecosystems expands, researchers and pest management practitioners are beginning to find ways of manipulating interactions across different trophic levels in order to develop more sustainable approaches to pest management. Accordingly, population ecologists are actively debating the relative importance of bottom-up (resource-driven) and top-down (natural enemy-driven) processes in the regulation of herbivores populations [22, 187, 188]. However, there are a number of key areas where manipulation of host plant-pest-natural enemy interactions could provide substantial benefits in pest management systems (manipulation of host plant quality, allelochemicals and crop diversification and genetic manipulation of insect) [26].

For many years, there was a widely held view that HPR should be seen as an integral component of IPM programmes, but it has been demonstrated that HPR is by no means always

compatible with biological control [178]. The significant and growing evidence from fundamental research in allelochemically mediated interactions hold substantial promise with regard to the development of novel IPM techniques. Allelochemicals mediated interactions in insect-host plant relationship have been recognized as the most important factors in the successful establishment of an insect species on a crop [189]. Furthermore, allelochemicals produced by plants also have considerable influence on the prey/host selection behavior of natural enemies, so that plants, herbivores, and natural enemies are interconnected through the well-knit array of chemicals. The host plant volatiles play a key role in attracting/repelling or retaining the natural enemies, thereby causing considerable changes in pest populations on different plant cultivars [190]. Hare [191] cited 16 studies where interactions between resistant cultivars and natural enemies (parasitoids) were studied and the outcomes show a spectrum of interactions, ranging from synergistic, to additive, to none apparent through to disruptive or antagonistic. Negative interactions can occur due to the presence of secondary chemicals that are ingested or sequestered by natural enemies feeding on hosts present on resistant or partially resistant plants [192]. For example, specific toxic components in partially resistant soybean plants can be particularly problematic in this regard [193]. In addition to allelochemicals, morphological traits of host plants such as trichome density and color complexion can affect insect fitness and effectiveness of its natural enemies. It was observed that plant cultivars were sufficiently differing in their trichome density and color complexion which were considered as main resource of variations in rate of parasitism on different plant cultivars. Cotton cultivars with low density of hairs on the upper leaf surface and high hair density on the lower leaf surface help in reduction of pest incidence [194]. The rates of parasitism were negatively associated with trichome density as revealed by Mohite and Uthamasamy [195]. In another study, Asifulla *et al.* [196] noticed higher parasitism by *T. chilonis* on *H. armigera* eggs in glabrous cotton species compared to hairy types.

In conclusion, as a novel strategy for IPM programmes, well understanding of multitrophic interactions is critical to develop the sustainable, less pesticide-dependent or pesticide-free pest management programmes [197]. In the interest of agricultural sustainability, tritrophic manipulation, as a distinct approach to biological or cultural control, is probably to be prioritized increasingly by both researchers and those responsible for the development and practical implementation of pest management programmes. This process will be facilitated if improvements in the understanding of crop-pest-natural enemy evolution and their interactions are achieved [26, 197]. Information in this regard are essential in finding out what role the plant play in supporting the action of natural enemies and how this role could be manipulated reserving the natural enemies.

11. Conclusion

Helicoverpa armigera represents a significant challenge to soybean cropping systems in many parts of the world and remain the target for concentrated management with synthetic insecticides. However, the extensive use of insecticides for combating *H. armigera* populations is of

environmental concern and has repeatedly led to the development of resistance in this pest as well as the deleterious effects on nontarget organisms and environment. The common trend towards reducing reliance on chemicals for control of insect pests in agriculture renewed worldwide interest in integrated pest management (IPM) programmes and it seems that in most areas the aim must be integrated management, particularly on crops such as soybean where *H. armigera* is part of a diverse pest complex. Accordingly, in this chapter we attempt to introduce basic elements for implementation of sustainable management of *H. armigera*. For this, we reviewed the main findings of different researchers and in some cases present our data. However, our findings revealed that for successful management of *H. armigera*, more attention should be devoted to some basic information such as monitoring efforts, forecasting activities and economic thresholds. In addition, more studies are needed to evaluate potential of novel control measures including selective insecticides and sublethal doses, HPR and genetically modified soybean cultivars and microbial pathogens (especially commercial formulations of *B. thuringiensis* and NPV) for control of this noctuid pest. However, for future outlook of integrated management of *H. armigera* in soybean cropping systems, the development and use of resistant cultivars will play a crucial role. In other words, more works should be conducted to evaluate resistance of soybean cultivars to *H. armigera* in field conditions. Moreover, a further need is to evaluate tritrophic interactions among the soybean cultivars, *H. armigera* and its natural enemies and new studies should be included to evaluate such interactions. However, the information gathered in the current chapter could be valuable for integrated management of *H. armigera* in soybean cropping systems.

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