Pest Management for Agronomic Crops

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Abstract

Agriculture is the main stay for many countries having agrarian economies in the world. Today there are major challenges to feed burgeoning population of the world. Among other causes of low productivity of agronomic crops, insect pests attack is also a major concern. However, under climate uncertainty, this issue has been much aggravated. This chapter focused that integrated pest management (IPM) proved to the best option to control insect pests of agronomic crops for increasing production and ultimately ensuring food security under climate change scenarios.

Keywords

Insect · Pest · Control · Integrated pest management · Cereals · Oilseed · Crops

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18.1 Introduction

Humans since the dawn of the agriculture have been competing with the animals for their effects on crops in terms of different types of losses. Insects outweigh all the other groups of the animals. The earliest record of the insect ravages dates back to 2625–2475 BCE from Egypt in the ancient times, when the locusts and other insects caused plagues (Ordish 1976). In the Middle Ages, little is known about the agriculture and pests; however, plagues due to locusts have also been recorded in this era. Moreover, cockroaches and rodents were noted as pests. Chinese also used bridges of bamboo sticks on citrus trees in about 800 AD to encourage predatory ants to move from one tree to another for biological control of insect pests. In the seventeenth century, there was more urbanization in Europe; therefore demands for food were increased. Consequently, due to urbanization more populations of insects were noted. Insecticidal properties of tobacco infusions and arsenic were discovered in the last part of the seventeenth century. Although people knew the toxic properties of the arsenic, the fear of hunger was more powerful than the toxicity. Here we discuss brief history of the pest management from eighteenth century to the modern times and pest management perspective of some important agronomic crops.

18.2 Pre-Insecticide Era

The important landmark in the biology was the introduction of the binomial system of the nomenclature in the eighteenth century by Carolus Linnaeus. The method of giving the standard names to the species helped in storage and retrieval of the information for biological pest control. The other important discovery was the understanding of connection between heat summation and various physiological processes of growth, development, and reproduction in insects. Scientists also came to know the plants' natural defense system against the insects which helped in increased development of botanicals. Insecticidal properties of nicotine, pyrethrin, and rotenone were discovered which are still used in pest management systems.

The first variety of apple resistant to woolly apple aphid was recorded in the UK in the beginning of the third decade of the nineteenth century. Scientists came to know that insects transported from one place to another can be pest through trade or tourism. Similarly if plants are introduced into place, the native species can also be the pests on newly introduced plant species. The grape *Phylloxera* a homopteran species was transported from North America to Europe and became serious threat for grapes in 1860s. This invasion led to first organized attempt of legislative measures to future invasion of the pests. Second decade of the twentieth century witnessed the resistance development in San Jose scale to lime sulfur. The term biological control was also coined in 1919 based on the concept that predators and parasitoids could control pest organisms.

18.3 Insecticide Era

The important landmark was the discovery of the insecticidal properties of DDT by the Swiss chemist Paul Muller in the era of the Second World War. This compound was discovered in 1874 in Germany as chemical, but its insecticidal properties were not known until 1940. Paul Muller was awarded the Nobel Prize in 1948. The production of the pesticides along with their applications in agricultural crops was increased tremendously in the 1950s (Osteen and Szmedra 1989). Newer chemical molecules were searched for their evaluation as insecticides to control the insect pests.

The earliest record of the insecticide resistance to synthetic chemicals dates back in 1946 DDT failed to control the houseflies in Denmark and Sweden (Brown and Pal 1971). Occurrence of resistance to insecticides led to the development of the new molecules which were introduced from time to time. After the discovery of insecticidal properties of organochlorines, organophosphates (OPs) and carbamates were discovered as insecticides. However, development of resistance to new molecules also went on parallel with their discoveries. The OPs completely replaced organochlorines to manage cotton pests in the early 1960s in Texas. Tobacco budworm, *Heliothis virescens* (Fabricius), was resistant to carbamates and OPs in the Lower Rio Grande Valley of Texas in the late 1960s (Perkins 1982). Resistance to OPs and carbamates was developed in *Helicoverpa armigera* (Hubner) during the early 1970s from Australia. Pyrethroids developed resistance to *H. armigera* only after 4 years of their introduction in Australia in 1979 (Forrester et al. 1993). The problem of the resistance was ubiquitous in the world to all classes of insecticides as well as diversity of the arthropod pests in 1990s (Razaq 2006). Insecticide resistance has been reported in 597 species of arthropods to 336 compounds in 14,644 cases from the world. *Plutella xylostella* (L.), *Bemisia tabaci*, and *H. armigera* are the species to which the highest numbers of compounds have developed resistance (www.irac-online.org/documents/resistance-database-team-update-2016).

Along with the resistance, other consequences of insecticides like emergence of secondary pests or replacement and resurgence were also observed. Cotton leaf perforator, *Bucculatrix thurberiella* Busck, was an obscure insect, but after the widespread use of DDT, it became major pest of cotton in the Imperial Valley (Smith and Flint 1977). Whitefly, *Bemisia tabaci* (Gennadius), was the secondary pest of cotton in Sudan and the Imperial Valley, but it became a major threat of the cotton only after the application of insecticides in both the regions. In Sudan yield of cotton decreased from 1653 kg/ha to 1020 kg/ha even after 600% increase in the cost of spraying (Johnson 1982).

Insecticides also affect the nontarget insects rendering the ecosystem services. Males of colonies of honey bees, *Apis mellifera* L., receiving neonicotinoids (clothianidin and thiamethoxam) have shown reduced reproductive capacity. As might be expected, queen failure and wild insect pollinator decline could be due to the effect of neonicotinoids on the male reproductive capacity (Straub et al. 2016). In the recent studies, it has been also proved that consumption of fruits and vegetables with high pesticide residues affects reproduction in humans (Chiu et al. 2015; Chiu et al. 2018). In China insecticide residues (of 32 insecticides) exceeded maximum residue limits detected from 20 vegetables (Yu et al. 2018).

18.4 Integrated Pest Management Era

Although consequences started to surround since the beginning of the chemical control, still all the problems prevail in almost all the regions where insecticides are applied. Stern et al. (1959) wrote a seminar paper entitled "The Integrated Control Concept" which is considered the basis of modern pest management. The concept was based on understanding of pest population development, sampling/monitoring, determining need/time for application of control measures, applying only selective insecticides, and integrating control methods. All these components are still required in any pest management system around the world. The authors emphasized that integrated control is not a panacea that can be blindly applied to any system. It was argued that our knowledge about agroecosystem alone is not sufficient to shift from intensive calendar-based application to integrated control. The effects of previous treatments of chemicals may last for several years. Moreover, biological control agents have to be reestablished where they no longer exist.

The integrated control was applied in various crops to control the pests in 1950 until 1960 like codling moth, *Cydia pomonella* (L.), and other pests on walnut. The efforts of integrating different control measures were adopted to address the problems of insecticide resistance, resurgence, and replacement. The entomologists thought to consider the whole picture of the entomology to control insect pests. Biotic factors like predators, parasitoids, and insect pathogens (bacteria, fungi, virus, etc.) causing diseases in insects were considered important to control insect populations. Likewise application of integrated control to crops the term also entrenched in the entomological literature (Michelbacher and Bacon 1952). However, the term pest management began to surface among specialists (Apple and Smith 1976). Both the terms integrated control and pest management coexisted in the literature as synonyms to each other until the middle of the 1970s. In the same decade, a term integrated pest management (IPM) was coined by the Panel of Experts of Food and Agriculture Organization (FAO). However, the term was discussed in several meetings of the committees of experts formed by the government of the USA and also in congresses of the entomologists. Several definitions of IPM were put forward, and till the last decade of the twentieth century, more than 60 definitions were proposed (Kogan 1998). However, well-accepted definition in the literature is of Kogan (1998), "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."

Recently it has been argued that IPM does not come under the true meanings of sustainable because it requires inputs of various control methods continuously.

Alternate terms "environmental pest management" or "ecological pest management" have been proposed to refer to truly sustainable solutions with the emphasis that, when these will be integrated into agricultural production systems, will function without any further human interventions (Coll and Wajnberg 2017; Shennan et al. 2004). In the current scenario, IPM concept has envisaged with a focus on all the components of agroecosystem and also takes into account the economic, marketing, social, and political factors those affect IPM adoption (Bottrell and Schoenly 2018).

Integrated pest management strategies were applied in both developed and developing countries. With all the efforts, insecticides became part of any pest management system, and it was not possible to totally abandon them from the agricultural systems. However the efforts were diverted to minimize their use and toxic effects. In most of the cases, IPM was developed to deal with the consequences of the insecticides. One of the most important issues was the development of insecticide resistance to insecticides. Cotton was the worst crop in all regions where grown with respect to development of resistance in its herbivores mainly due to economic concerns. Before the introduction of the genetically modified cotton, lepidopterans belonging to genera *Heliothis* and *Helicoverpa* (Lepidoptera: Noctuidae) were almost resistant to all the available insecticides in the USA, Australia, China, Africa, India, and Pakistan (Razaq 2006).

IPM strategies had varied success in developed countries but largely failed in the majority of cases in developing countries, mainly due to lack of knowledge among the growers for compliance and also research to develop the IPM guidelines in the agroecosystem in which they exist. *Helicoverpa* spp. became resistant to the pyrethroid insecticides only 4 years after their introduction in Australia in 1983 (Forrester et al. 1993). Insecticide resistance management (IRM) strategy was developed to extend susceptibility of pyrethroids, as previously these pest species developed resistance to insecticides belonging to organochlorine, organophosphate, and carbamate groups of insecticides. The insecticide resistance management strategy based upon the rotation of unrelated chemical groups on per generation basis was implemented. Pyrethroids were allowed to spray on cotton for 42 days in mid season. The resistance was continuously monitored by discriminating dose technique based upon the larvae reared from the field-collected eggs. Later on from 1989 to 1990, pyrethroid window was reduced to 35 days. It was thought that two main reasons were contributing for reduction in resistance, i.e., susceptibles immigrating from refugia and pyrethroid selection pressure (Forrester et al. 1993). This strategy undoubtedly held pyrethroid resistance in check for number of years. But there was steady rise in proportion of population that was resistant to pyrethroids. The Australian IRM strategy was imitated and applied with successful outcomes in many agroecosystems of the world like management of *B. tabaci* in the USA (Castle et al. 1999; Ellsworth and Martinez-Carrillo 2001).

18.5 Era of Genetically Modified Crops

The major breakthrough in the history of the IPM was development of the genetically modified (GM) crops to manage insect pests and weeds. The gene of *Bacillus thuringiensis* Berliner (Bt) has been inserted in the crop plants to manage insect pests belonging to insect order Lepidoptera. Other genetically engineered crops are those which are tolerant to specific herbicides (particularly to glyphosate and to glufosinate) in cotton, canola, maize, and soybean. The plants having resistance genetically modified herbicide-tolerant (GM HT) traits allow for the spraying of such crops with broad-spectrum weedicides, to manage both the broad-leaved and narrow-leaved weeds, but do not affect the crops themselves (Brookes and Barfoot 2017). Such crop varieties were released for commercial cultivation in the last decade of the twentieth century (Naranjo 2010). Currently, genes have been stacked in some crops for both the insect resistance and herbicide tolerance.

The area under GM crops is 12% of the total agricultural crops in the world, in which 40% of these crops are grown in developing countries. Genetically modified cotton occupies 75% of the total area under cotton in the globe (Eisenring et al. 2017). These crops have reduced the 581.4 million kg of the pesticides ultimately decreasing their adverse environmental impacts. These crops have also helped in reducing fuel needed to apply the pesticides and for tillage to manage weeds resulting in decrease of the greenhouse emissions from GM cropping area. It has been estimated that in the year 2014, it was equal to decreasing ten million cars from the roads (Brookes and Barfoot 2017). Increases in grain yield and quality and decreases of the target insect *Diabrotica* spp. have been recorded in the last 21 years of its cultivation from maize. Moreover, these crops had low or no effect on the population abundance of nontarget insect and also reduce mycotoxin contents in grain minimizing economic losses in the world (Pellegrino et al. 2018).

However, the cultivation of the GM cotton witnessed problems like evolution in insects to develop resistance against genes conferring it and appearance of new hemipeteran insect pests. Since the inception of the GM cotton, efforts were directed toward managing resistance. Resistance has been successfully managed particularly by pyramiding genes and planting of susceptible refuge crop (non-Bt) to manage pink bollworm (PBW), *Pectinophora gossypiella* (Saunders), in the USA. Similarly *H. armigera* has also been managed without any losses to growers by aforementioned tactics and with some other cultural practices in Australia (see also section for “Cotton Pest Management”). Moreover Bt cotton have been failed due to development of resistance in PBW, which has become again threatening pest in China, India, and Pakistan. The major reason for its success in the developed nations is the development of strategies and their 100% compliance by the farmers to delay evolution of resistance, whereas no such strategies were employed in the developing nations.

Different control methods like cultural control, mechanical control, host plant resistance, and biological control need to be integrated in harmonious way.

18.6 Components of IPM

Around 60 years have gone by ever since the concept of integrated control was introduced by Stern et al. (1959). Idea behind this concept was to integrate insecticides and biocontrol agents in such a way that insecticides affect biocontrol agents as least as possible. For that, four basic elements, which had to be strategically assembled, were introduced. These included (1) determining thresholds for deciding control action, (2) sampling plans for assessing critical densities, (3) impact of biocontrol agents on pest suppression, and (4) the use of selective insecticides. According to Naranjo and Ellsworth (2009), integrated control concept has been the driving force in shaping up the conceptual frame work of IPM. IPM is a diverse set of various chemical and nonchemical pest control actions adopted in harmony, and insecticides must be applied when other control methods are failure.

IPM today has been dominated by single technology intervention, particularly insecticides (Thomas 1999), and originally it should consider ecological interactions of other pest control tactics. Foundation of IPM should primarily be based upon thorough understanding of individual ecology and ecological interactions between pests, biological agents, and host crop (Fitt 2000). Understanding these ecological aspects provide opportunities in exploring and integrating other pest control tactics like cultural control, host-plant resistance, and habitat manipulation (Cook et al. 2007; Douglas 2018; Shakeel et al. 2017). Moreover, emerging era of genetically modified crops (Kennedy 2008), which in integration with other nonchemical tactics, have been found effective in developing sustainable and economically acceptable IPM package, with much less reliance on pesticides (Fitt 2000). The modern IPM, which has evolved through hands and minds, has therefore gone far beyond the bounds of integrated control concept, latter mainly focused insecticides and biological agents of pest control.

Here we take the case of whitefly, *Bemisia tabaci*, as a polyphagous pest and a menace to a range of agronomic and horticultural crops, worldwide. In developing IPM against this pest, Ellsworth and Martinez-Carrillo (2001) focused three key elements including sampling, effective use of chemicals, and pest avoidance. These elements were the building blocks of IPM and represent an excellent overview of IPM components. Ellsworth and Martinez-Carrillo (2001) in their work piled these elements over each other to build a pyramid. The pyramid is a paradigm representing arrangement of elements and set of actions within each element. In this pyramid, sampling resides apex section, while avoidance and effective chemical use reside bottom and middle sections, respectively. However, variation can occur in their level of implementation.

18.6.1 Sampling

Sampling is a method of classifying population abundance of a given pest species. Sampling is used for detecting pest presence or measuring its damage – this information is subsequently utilized for deciding intervention. While sampling can vary according to species, therefore suitable sampling methods should be adopted after careful consideration. Without a well-designed sampling method, it is unlikely to have near accurate estimation of pest situation, and this also questions accountability of intervention used. Thus, sampling has tremendous impact in determining the fate of pest management and should be adopted carefully for successful implementation of IPM.

18.6.2 The Effective Use of Chemicals

This component considers three major strategies: (1) action thresholds for deciding intervention, (2) choice and effectiveness of insecticides, and (3) insecticide resistance management. Insecticides are the integral part of IPM; however, they should be used when other pest control strategies are unable to suppress pest. Insecticides should be applied when the pest has reached densities, which are damaging (i.e., action threshold). As their use is associated with nontarget effects, replacing broad-spectrum insecticides, which target wide range of insects, with selective insecticides, can conserve beneficials. Highly selective and toxic insecticides may result in complete elimination of pest, which can deprive biocontrol agents of their prey and favors inter- and intraguild predation. Further, caution is needed while selecting insecticides, because frequent use of insecticides favors natural selection in pest. This may led to insecticide resistance development in pest populations. One vital way to overcome resistance is developing and rotating new chemistries in varying mode of actions.

18.6.3 Avoidance

This is the bottom part of the pyramid and the most complex one. It deals with a wide range of pest control strategies considering crop management practices, pest biology and ecology, and area-wide management. All these are a complex set of interaction working in a way to shift competitive advantage to host over pests. These set of actions that in part, serve to keep the pest below damaging level, represent avoidance.

18.7 Pest Management in Cotton

Upland cotton, *Gossypium hirsutum* L., occupies 95% area in the world among other species. Due to the economic concerns, cotton has been exotic crop in most parts of the world; therefore, insect complexes have invaded this crop in different production systems (Castle et al. 1999; Naranjo 2010). More than 1300 arthropod species have been recorded from cotton around the globe; however, about 3 dozen species are considered as regular pests (Naranjo 2010; Trapero et al. 2016). Insect pests damaging to the cotton mainly belong to the two categories, i.e., sucking insects and bollworms. Sucking insect pests belong to the orders Hemiptera (bugs and whiteflies) and Thysanoptera (thrips) and feed on the sap. The second group belongs to the insect order Lepidoptera and their immature stages or larvae feed mostly upon the reproductive parts of the plants. Other than these two groups, insect pests include weevils, termites, crickets, grasshoppers, etc.; these insect pests are specific to the regions of the world. The earliest record of heavy losses from the insect pests to cotton dates back to the last decade of the nineteenth century by the boll weevil *Anthonomus grandis* Boheman in the USA (Frisbie et al. 1994).

Since the discovery of synthetic insecticides from the 1940s, insect pests of cotton have been managed with them. Due to the sole reliance on these chemicals, consequently their associated impacts have resulted in the development of resistance in arthropods, appearance of secondary pest, and resurgence of the species being targeted. Resistance to insecticides was reported as early as in the 1950s, and the numbers of arthropod species being resistant increased temporally. In the 1980s resistance to variety of insecticides was recorded in 26 insect pest species of cotton herbivores (Georghiou and Mellon 1983). In the last decade of the twentieth century, the silverleaf whitefly *Bemisia tabaci* (Genn.) and bollworms (*Heliothis* and *Helicoverpa* spp.) were resistant to the almost all the conventional insecticides, and their susceptibility was also being lost to new chemistry insecticides in the USA, Australia, and Asia (India, Pakistan, and Thailand) (Castle et al. 1999; Razaq 2006).

Genetically modified cotton varieties those express the toxin of *Bacillus thuringiensis* (Bt), which controls lepidopteran pests (bollworms *Heliothis* or *Helicoverpa* spp., *Pectinophora* sp., and *Earias* sp.), were introduced in 1995 for commercial cultivation. Bt cotton helped in managing resistant populations of bollworms that were not being controlled with insecticides (Wilson et al. 2004). In 2013, Bt cotton approximately occupied two third area of the total area in the world (James 2015).

After the introduction of Bt cotton, there was substantial reduction in insecticide use with negligible effects on nontargets (Whitehouse et al. 2014). Until 2008, 141 million kilograms of synthetic insecticides were saved, and those were applied to manage bollworm species before the adoption of Bt cotton. In the USA 44% reduction in insecticides was recorded on Bt cotton as compared to pre Bt era. In Australia after the introduction of Bollgard II, 80–90% to 65–70% reductions in the active ingredients per hectare were noted (Naranjo 2010; Fitt and Wilson 2012).

The primary challenge to the continued success, which was given due consideration even before the introduction of the genetically modified cotton, was the evolution of resistance by insect pests (Carpenter 2010). Populations of the *Helicoverpa armigera* (Hubner), *Helicoverpa punctigera* (Wallengren), *Heliothis virescens* (F.), and *Pectinophora gossypiella* (Saunders) from Australia, China, and the USA during the first 22 years after the introduction of Bt cotton have been recorded to sustain susceptibility against genetically modified cotton varieties. Susceptibility in the target species of the Bt cotton was due to adoption of preemptive insecticide resistance management (IRM) strategies (Catarino et al. 2015). However in developing countries, where IRM strategies were not developed or even in the regions where farmers did not comply with guidelines of Bt resistance management program, cotton crop had reached to crisis phase due to development of resistance in target herbivores. In India and Pakistan, *P. gossypiella* is a redundant pest of Bt cotton only due to the development of resistance in the absence of the IRM strategies (Mohan et al. 2016).

Integrated pest management requires continuous stewardship to sustain its effectiveness, which requires research as well as extension services and their compliance (Bottrell and Schoenly 2018). Here we briefly discuss the success of Bt cotton in the USA and Australia due to both aforementioned reasons. To counter the resistance first of all pyramids of Bt crop were developed Bt toxin to those expressing two or more Bt toxins. This combination of toxins is called "pyramiding." The Bt varieties of cotton were developed having Cry1Ac and Cry2Ab toxins. Pests resistant to toxin Cry1Ac were susceptible to Cry2Ab; moreover, there was no cross resistance across the two toxins, as both these toxins have different binding sites in the midgut of the larvae (Carrière et al. 2006; Tabashnik et al. 2009).

The resistance to *P. gossypiella* has been encountered by developing and adoption of the refuge strategy by the growers in the USA. In this strategy farmers have to plant specified area of the non-Bt cotton with Bt cotton (Huang et al. 2011). This strategy provides Bt-resistant pests chances of random mating with abundant populations of Bt-susceptible pests from the susceptible refuge crop, thus reducing the chance of selection of Bt-resistance in pest populations. Moreover, several studies proved that Bt-resistance in Cry1Ac and pyramids of Bt cotton in *P. gossypiella* is a recessive trait, therefore all heterozygotes will die when they will feed on cotton plants having Bt toxin. The resistant individuals are also biologically deficit on non-Bt plants of the cotton crop (Carrière et al. 2015; Fabrick et al. 2015; Gassmann et al. 2009). Release of sterile moths in cotton fields of cotton in the USA in 2006 also contributed in delaying resistance in *P. gossypiella* (Tabashnik et al. 2012).

In Australia, resistance development has been delayed in *H. armigera* and *H. punctigera* with a preemptive IRM strategy. This strategy include the following: (1) it is compulsory to grow 10% of non-sprayed refuge crops of non-Bt cotton; (2) destruction of ratoon crop plants; (3) planting cotton recommended time; (4) minimizing sowing of Bt cotton expressing foliar toxins; and (5) obligatory to destroy pupae of both the species of *Helicoverpa* when the crop is over (Baker et al. 2008). The major reason for the success of sustained susceptibility was complete compliance of the growers with recommendations besides increasing their cost of production and inconvenience particularly for size and distance of sowing of non-Bt cotton in Australia and in the USA, respectively (Carrière et al. 2004; Wilson et al. 2004).

The second problem with Bt cotton was the emergence of sucking pests (e.g., the bug complex) when the insecticides used against lepidopteran bollworms were reduced, which had indirectly controlled these secondary pests. These emergent pests were managed coincidently with the insecticides that had been used to manage bollworms. The reliance on insecticides to control these sucking pests since the introduction of Bt cotton led to the problem of resistance in these pests in Australia (Trapero et al. 2016).

Commercial plantation of Bt cotton also suffered from substantial increase in the damage by secondary pests due to reduction in use of pesticides applied to manage lepidopteran pests in Australia, China, India, and Pakistan (Lu et al. 2010; Naranjo

2010; Saeed et al. 2015; Wilson et al. 2013). These secondary pests belong to the Hemiptera (aphids, leafhoppers, and bugs). These pests are being managed with proper use of insecticides and with other (IPM) tactics, with no further problems in the USA (Catarino et al. 2015).

18.8 Pest Management in Cereal Crops

Cereal crops are grown for their edible starchy seeds and by far considered to be the most important source of concentrated carbohydrates both for humans and animals (Leonard and Martin 1963). Cereals are the main items in the diet of much of world's population and accounts for the 70% of harvested acreage in the world (Janick et al. 1969). Cereals including wheat and corn are being utilized for food and feed and also as biofuels (e.g., ethanol) (Wolf et al. 2018). There are many insect pests reported to infest underground and aboveground parts of wheat including Hessian fly, *Mayetiola destructor* (Say), in the USA (Gallun et al. 1975); wheat stem sawfly, *Cephus cinctus* (Norton), in North America (Weiss and Morrill 1992); sunn pest, *Eurygaster integriceps* (Puton), in West and Central Asia and East European countries (El Bouhssini et al. 2009); cereal leaf beetle, *Oulema melanopus*, in Tajikistan (Landis et al. 2016); the orange wheat blossom midge, *Sitodiplosis mosellana* (Gehin) (Diptera: Cecidomyiidae), in the northern hemisphere (Chavalle et al. 2015); saddle gall midge, *Haplodiplosis marginata* (von Roser), in Belgium and several other European countries (Censier et al. 2016); and several species of aphids (Hemiptera: Aphididae) including English grain aphid, *Sitobion avenae* (Fabricius); corn leaf aphid, *Rhopalosiphum maidis* (Fitch); bird cherry-oat aphid, *Rhopalosiphum padi* (L.); greenbug, *Schizaphis graminum* (Rondani) (Walker); *Rhopalosiphum rufiabdominale* (S.) (Hashmi et al. 1983); and Russian wheat aphid, *Diuraphis noxia* (Mordvilko) (Inayatullah et al. 1993).

Among these species, aphids are considered as the most severe pest of wheat crop in Asian countries as well as across the globe. Three species, *Sitobion avenae* (F.), *Rhopalosiphum padi* (L.), and *Schizaphis graminum* (R.), are major insect pests of wheat (Kannan 1999; Shah et al. 2017). Aphid inflicts significant economic losses to wheat and other cereals by direct feeding on phloem sap (Kindler et al. 2002) or indirectly by carrying and spreading plant viruses, especially barley yellow dwarf virus between crops (Gray et al. 1996). Moreover, secretion of honeydew on leaves interferes with photosynthetic and respirational functions of plants and consequently boosts leaf senescence (Bardner and Fletcher 1974). Aphids can cause 35–40% loss directly by sucking sap and 20–80% indirectly by transmission of fungal and viral diseases (Kieckhefer and Gellner 1992; Rossing et al. 1994).

Biocontrol agents such as parasitoids, lady beetles, hover flies, green lacewing, and spiders can considerably contribute to the pest management worldwide (Ali et al. 2018; Saeed and Razaq 2015). In Pakistan, coccinellids, mainly *Coccinella septempunctata* L. and *Coccinella undecimpunctata* L. (Coleoptera: Coccinellidae); syrphids, mainly *Ischiodon scutellaris* F. (Diptera: Syrphidae); spiders, mainly *Oxyopes javanus* T. (Araneae: Oxyopidae) and *Pardosa birmanica* S. (Araneae:

lycosidae); and aphid parasitoids, *Aphidius colemani* V. (Hymenoptera: Braconidae), are the important aphid natural enemies (Shah et al. 2017). Natural enemies may act as strong top-down forces in suppressing aphid population. However, predator efficiency and their development are affected by various factors such as competency for prey resource, intraguild predation (Mirande et al. 2015), and/or temperature (Ali et al. 2014), which under unfavorable circumstances could compromise predator efficiency. As the aphids can inflict huge economic losses, various studies have evaluated synthetic insecticides against wheat aphids (Shahzad et al. 2013; Wang et al. 2017). Insecticides have been evaluated along with cultural practices, such as through the involvement of planting dates (Royer et al. 2005; Shahzad et al. 2013). However, due to concern on synthetic chemical use in wheat, the current emphasis on developing environment-friendly pest control alternative such as integrating azadirachtin-based neem-derived products in pest management. Neem-derived compounds have been found promising and compatible with natural enemies (Aziz et al. 2013) and even can increase the susceptibility of pest toward biological control agents by affecting diverse array of performance-related parameters of target pests (Charleston et al. 2006).

18.9 Pest Management in Oilseed Crops

The oilseed crop sector is regarded as a most dynamic parts of world agriculture that grew at 4.3% as compared with an average of 2.1% for all agriculture until first decade of the twenty-first century. One of the reasons for the growth of this sector is the use of vegetable oil for non-food purposes particularly in industries. However, the major reason for the rapid growth of oilseed crops is their consumption as food in the developing countries due to high-calorie contents of oil products (Alexandratos and Bruinsma 2012). Soybean, oil palm, rapeseed, sunflower, groundnut, coconuts, cotton seed, and sesame seed are the oilseed of the world (Alexandratos and Bruinsma 2012).

Developing countries cannot meet their total requirements of the oil from their domestic production; therefore they need the import of the edible oil. Rapeseed crops rank third in the world among all the other crops; moreover, these are also important in developing countries as these are used for multiple purposes like fodder, humans food (both as plants and oil), and cattle feed in the form of the oilseed cake. Canola, *Brassica napus* L., is also grown in almost all the continents. Here we shall focus on the pest management problems of the rapeseed and mustard and particularly those of *B. napus*.

Rapeseed and mustard crops are invaded by the variety of the insect pests. However, their damage varies in the different countries where these are grown. In Australia, 30 species of the arthropods have been recorded. The insect pests belong to the insect orders Hemiptera (aphids, bugs), Lepidoptera (*Helicoverpa punctigera*, *Plutella xylostella*), and Coleoptera (*Phyllotreta cruciferae*) (Aslam and Razaq 2007; Gu et al. 2007; Tangtrakulwanich et al. 2014).

Cabbage aphid, *Brevicoryne brassicae* (L.); turnip aphid, *Lipaphis erysimi* (Kaltenbach); and green peach aphid, *Myzus persicae* (Sulzer), are the primary insect pests of oilseed *Brassica*. These have been reported to cause damage in 33 states of the USA and several Asian countries, such as Bangladesh, Iran, India, and Pakistan (Adhab and Schoelz 2015). In case of the severe infestation, these aphid species may cause complete failure of the crop particularly from Asian countries with up to 11% reduction in oil contents.

Although aphids can feed on all the reproductive parts of the plants, reproductive parts like rosettes and flowers are preferred. Aphid feeding on *Brassica* crops at vegetative stage distorts leaves, prevents vegetative growth of plants, and inhibits flowering and finally pod formation (Gu et al. 2007; Weiss 1983). Damage at flowering stage causes wilting of flowers as *Lipaphis erysimi* and *B. brassicae* reduce photosynthetic rate and chlorophyll contents Razaq et al. 2014; (Hussain et al. 2015).

Among the nonchemical control methods, rigorous screening attempts in India and Pakistan proved lack of the resistance in the varieties development programs. Many species of the coccinellids and chrysopids are reported as the predators of the aphids (Amer et al. 2009). Among the parasitoids *Diaeretiella rapae* (M'Intosh) is reported from the different parts of the world. But both these kind of natural enemies are unable to keep the populations of aphids below the status of the pest (Aslam and Razaq 2007). Action threshold levels can reduce enormous quantities of insecticides need to determined yet.

18.10 Pest Management in Pulses

Pulses are the second only to the cereals and the important source of proteins in the human diet, predominately for the world's vegetarian population (Kochhar 2016). Several crops such as pea (*Pisum sativum* L.), lentil (*Lens culinaris* Medic.) and chickpea (*Cicer arietinum* L.), pigeonpea (*Cajanus cajan*), mungbean (*Vigna radiata*), and urdbean (*Vigna mungo*) are the important pulse crops grown in the USA and Asian countries. While pulses are attacked by a great diversity of insects, a few in these are economically important, and the economic status of pests may vary geographically (Singh and Emden 1979). In the USA and Canada, several pest species are characterized as major pests of pulses. These include seedcorn maggot (*Delia platura* Meigen), a complex of wireworms (*Limonius californicus* (Mannerheim), *Limonius infuscatus* Motschulsky, *Limonius canus* LeCount, *Hypnoidus bicolor* Eschscholtz, *Aeolus mellillus* Saylor, and *Selatosomus aeripennis* Kirby), cutworms (*Euxoa auxiliary* Guenée, *Agrotis orthogonia* Morrison, and *Feltia jaculifera* Guenée), pea leaf weevil (*Sitona lineatus* L.), pea aphid (*Acyrthosiphon pisum* Harris), lygus bugs (*Lygus hesperus* Knight and *Lygus lineolaris* Palisot de Beauvois), and grasshoppers, mainly the omnivorous *Melanoplus sanguinipes* Say, *Melanoplus differentialis* Thomas, *Melanoplus bivittatus* Say, and *Camnula pellucida* Scudder (Jaronski 2018). In Asian countries, pulse are attacked by borer, *Helicoverpa armigera*; pod bug, *Clavigralla gibbosa*; pod fly, *Melanagromyza obtusa*; blister beetle, *Mylabris* spp.; hairy caterpillars, *Spilosoma* *obliqua* and *Amsacta moorei*; jassids/leafhoppers, in particular *Amrasca biguttala biguttala* (Ishida) (*Amrasca devastans* Dist.) (Hemiptera: Cicadellidae) (Soundaryarajan and Chitra 2012); termites, *Odontotermes obesus* and *Microtermes obesi*; pod borer, *Etiella zinckenella*; and, whitefly, *Bemissia tabaci* (Roshan and Rohilla 2007). Feeding damage by these species may occur on aboveground plant parts of the infested plants such as on the roots, root nodules, pods, flowers, and seeds (Knodel and Shrestha 2018) as well as belowground plant parts by soil-dwelling pests (Zvereva and Kozlov 2012).

Pea leaf weevil, *Sitona lineatus* L., is a serious pest of peas and faba beans (Cárcamo et al. 2018). *Sitona lineatus* is a univoltine species. Adult stage passes winters in state of quiescence alongside field margin. Adults, at the time of emergence, are oligophagous on several members of Fabaceae (Landona et al. 1995), whereas their reproductive phase has a clear preference for faba bean (Nielsen and Jensen 1993) and peas (Landona et al. 1995). Characteristics symptoms of adult feeding appear as U-shaped notches along the leaf margins (Jackson and Macdougall 1920); however, their infestation can rarely destroy young shoots (Williams et al. 1995). However, larval stage is critical, in addition to feeding on nodules, and larvae can feed on nitrogen-fixing bacteria within root nodules, thus reducing nitrogen availability for the infested plant (Cárcamo et al. 2015). Larvae are abundant in numbers, reaching up to 5000 per m^2 in field plots in southern Alberta, and their infestation may lead to destruction of approximately 90% nodules (Cárcamo and Vankosky 2011).

To avoid damage by pests, cultural, biological, and chemical control methods have been developed. For the cultural control, adapting crop rotation has been a key component of traditional pest management. As *S. lineatus* adults are very mobile and can move between fields, it is crucial to maintain reasonable distance between fields within seasons (Vankosky et al. 2009). Another approach that has been investigated against this pest for over 20 years has been employing crop plant resistance to manage this pest. Field pea varieties have varying amount of wax layers on leaves due to genotypic variation (Chang et al. 2004; White and Eigenbrode 2000), and manipulation of these genotypes may have potential in producing resistant varieties. *S. lineatus* prefers leaves and stipules with thinner wax layer compared to those that have thicker wax layer (White and Eigenbrode 2000). In Europe and elsewhere between 1960 and 1980, a significant amount of work was done in an effort to identify and develop field pea with *S. lineatus* resistance (Auld et al. 1980; Tulisalo and Markkula 1970), but these efforts met with limited success (reviewed by Vankosky et al. (2009)). New field pea and faba bean varieties and new tools for screening and introducing genetic-based resistance into plant populations may allow plant breeders to overcome past hurdles. Other avenues of investigation with respect to host plant resistance may include studying the effects of plant volatiles that modify pest behavior.

Another promising approach employed against *S. lineatus* is the utilization of biological control agents. These include several species of parasitoids, predators, entomopathogenic fungi, and nematodes. Although, none of the identified biological control agent of this pests is a specialist, however, a few species of parasitoid attacking *S. lineatus* in its native range have been released in North America for management of other *Sitona* spp. and other weevil species [e.g., *Hypera postica* (Gyllenhal) Coleoptera: Curculionidae]; however, their establishment was variable (Loan 1975). The most promising was *Anaphes diana* (Girault; Hymenoptera: Mymaridae), an egg parasitoid of *Sitona* weevils that was established in the eastern USA (Dysart 1990). No parasitoids attacking *S. lineatus* have yet been found in Alberta where the pest has been present since at least 1997 (Vankosky et al. 2009). There is no biological control program for any *Sitona* species, in Canada (Cárcamo and Vankosky 2013). The impact of generalist predators on *S. lineatus* populations is not well documented.

Several insecticides have been evaluated for the management of this species since 1980s. Earlier, foliar insecticide active ingredients were evaluated, and these include phorate (King 1981), cyhalothrin-lambda (Van De Steene et al. 1999), permethrin (McEwen et al. 1981), and imidacloprid (Van De Steene et al. 1999). Several other compounds such as carbaryl, cyfluthrin, phosmet, and cypermethrin are available depending on the jurisdiction. For example, in North Dakota as of 2017, the list included over ten active ingredients or mixtures. Foliar insecticides can reduce adult weevil populations and foliar damage, but may not protect yields (Vankosky et al. 2009). Cyhalothrin-lambda treatment reduced adult weevils by 56% (Van De Steene et al. 1999). Application of permethrin (pyrethroid insecticide) decreased larval populations by approximately 50% (Bardner et al. 1983), likely due to mortality of adult females, as contact foliar insecticides have no direct impacts on eggs or larvae (Van De Steene et al. 1999). Some products have improved yields only slightly. For example, plots treated with permethrin yielded 2.4% more than untreated plots (Bardner et al. 1983). Properly timing the application of foliar insecticides is difficult, as they must be applied immediately following the detection of weevil invasion to prevent adult females from laying eggs in the host crop (Bardner et al. 1983; King 1981). To ensure adequate plant protection, multiple foliar applications may be required over the course of the dispersal period of *S. lineatus*, depending on the residual time of the insecticide product and rainfall events. For these reasons, producers generally favor the use of systemic insecticides for management of this pest.

Another method is coating seeds with systemic insecticides for *S. lineatus* management in field peas. There is consensus that systemic insecticides are more effective than foliar applications (Dysart 1990). Many of the seed treatments such as carbofuran or related compounds, effective in Europe 30 years ago, are no longer available in most jurisdictions. Over the last two decades, these compounds were replaced by neonicotinoids, which in turn have been restricted in some jurisdictions or phased out. In western Canada and the USA, for now, neonicotinoids are still used in field peas, and its mechanism of crop protection is well known at least for thiamethoxam (CáRcamo et al. 2012). This chemical only kills around 30% of the adults, but there is a significant reduction in adult feeding damage (50%), less oviposition by survivors, and only about half of the larvae survive in plants grown from seeds coated with this chemical (CáRcamo et al. 2012). The authors cautioned that under situations of high weevil outbreaks, the surviving larvae still cause damage to reduce yields of peas, and this may explain the inconsistent yield protection observed in some studies (e.g., Vankosky et al. 2011).

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