Chapter 20
Insect Resistance

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Abstract Studies to-date have shown the availability of enough genetic diversity in the wheat genetic resources (land races, wild relatives, cultivars, etc.) for resistance to the most economically important insect pests such as Hessian fly, Russian wheat aphid, greenbug, and Sun pest. Many R genes – including 37 genes for Hessian fly, 11 genes for Russian wheat aphid and 15 genes for greenbug – have been identified from these genetic resources. Some of these genes have been deployed singly or in combination with other genes in the breeding programs to develop high yielding varieties with resistance to insects. Deployment of resistant varieties with other integrated management measures plays key role for the control of wheat insect pests.

Keywords Breeding · Gene introgression · Insect resistance

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20.1 Learning Objectives

- To understand the most important wheat insect pests, their geography, the mechanisms of insect resistance and breeding for insect resistance.

20.2 Introduction

The demand for wheat is increasing along with the increasing human population, and is expected to surge to one billion tons by the year 2050 [1]. Fulfilling this demand with the increasing impact of climate change, likely environmental and resources degradation, reduced supply and increasing cost of inputs, and emergence of new virulent pests will be challenging unless we deploy efficient strategies, methods and policies to develop climate smart wheat technologies with high genetic gain and minimum yield losses. Globally, wheat yield losses of 5.1 and 9.3% have been reported due to insect pests during the pre-and post- green revolution era, respectively [2]. This chapter summarizes the most important wheat insect pests, their geographic distribution and economic importance, sources and mechanisms of resistance, gene introgression, breeding methods and approaches for insect resistance.

20.3 Major Wheat Insect Pests, Geographic Distribution and Economic Importance

There are many insects affecting wheat production at global and regional levels. The major ones are Hessian fly, sunn pest, Cereal leaf beetle; Wheat stem sawfly, Russian wheat aphid, Greenbug, Bird Cherry-Oat Aphid, English grain aphid and Orange wheat blossom midge (Fig. 20.1). The biology, geographic distribution and their economic importance are indicated in Sections 20.3.1 to 20.3.9.

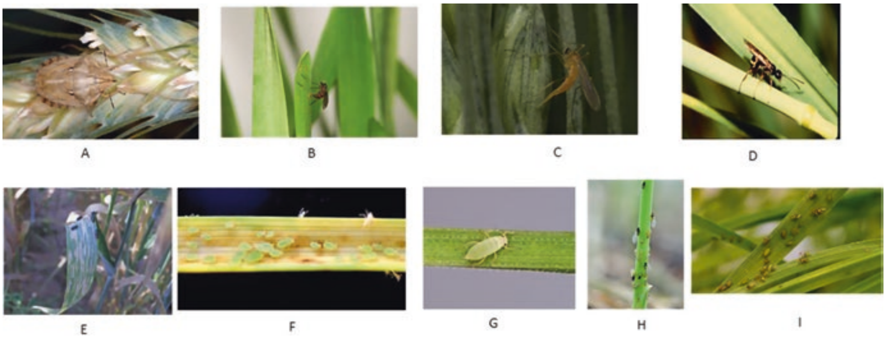

Fig. 20.1 Major wheat insect pest: (**a**) Sunn pest; (**b**) Hessian fly; (**c**) Cereal leaf beetle; (**d**) Wheat stem sawfly; (**e**) Russian wheat aphid; (**f**) Greenbug; (**g**) Bird Cherry-Oat Aphid; (**h**) English grain aphid; (**i**) Orange wheat blossom midge

20.3.1 Hessian Fly (Diptera: Cecidomyiidae)

Mayetiola destructor (Say) is an important pest of wheat in North Africa, North America, Southern Europe, Northern Kazakhstan, Northwestern China, and New Zealand. Yield losses of 30% are common but there can be complete crop failure if infestation coincides with young stage of the wheat crop [3]. Hessian fly adults are small (less than 1/8 inch long) and do not feed and do not live long. Females lay from 100 to 300 eggs. The pest has three larval instars. The first induces a gall nutritive tissue at its feeding site. The second grows rapidly. The third completes its development in a puparium that looks like a flax seed, which is where the pupa also lives. Hessian fly has a facultative diapause during the third instar and overwinters in wheat stubble or volunteer wheat. Depending on environmental field conditions, Hessian fly can complete 2–3 generations/year.

20.3.2 Sunn Pest

Sunn pest (Fig. 20.2) refers to several species in two genera *Eurygaster* and *Aelia*. The most widespread and damaging species to wheat is *Eurygaster integriceps* Puton (Hemiptera: Scutelleridae) which is about 12 mm long in size. Sunn pest is widespread throughout South and East Europe, North Africa, Near East, West and South-Central Asia. Yield losses attributable to direct feeding typically range between 50% and 90% [4, 5]. Prolyl endoproteases injected into the grain during feeding severely compromise the quality of the resulting flour by degrading the vital gluten proteins [6]. Sunn pest has one generation per year. Adults overwinter mainly in mountains and hills surrounding wheat fields. In early spring, mature

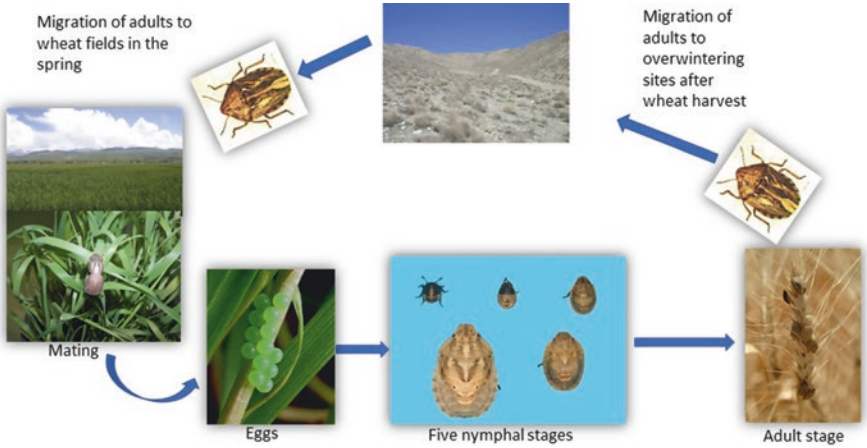

Fig. 20.2 Life cycle of Sunn pest

adults migrate from the overwintering locations to cereal fields. The pest has five nymphal stages, only four of which feed (2nd to 5th). Sunn pest incidence occurs in multi-year cycles, and when it happens, it is devastating. In a 2 ton wheat crop, the presence of 2 insects per m^2 can destroy baking quality of the total harvest [Dr. Hans-Joachim Braun, personal communication, May 24, 2021].

20.3.3 Cereal Leaf Beetle (Coleoptera: Chrysomelidae)

Oulema melanopus (L.) with average size of five millimeters (3|16 inch) length, is a significant pest of wheat in Europe and Central Asia but has been reported causing damage in several other parts of the world including Algeria, Tunisia, Morocco, Syria, India, Pakistan, Iran, United States and Canada. Yield losses in a single field can be as high as 55% in spring wheat and 23% in winter wheat [7], though damage is mostly locally confined. Larvae are more damaging than adults and have been reported to consume plant biomass 1 to 10 times their body weight. Cereal leaf beetle has one generation per year. Adult beetles overwinter in protected areas such as wind rows, crop stubble and tree bark crevices. Larvae go through four instars.

20.3.4 Wheat Stem Sawfly (Hymenoptera: Cephidae)

Wheat stem sawfly (WSSF) is the common name of a number of sawfly wheat pest species in North America, Europe, North Africa and Asia with average adult insect size of 3/4 inch length**.** In North America, the most important species is *Cephus cinctus* Norton. Yield losses inflicted by this pest in the Northern Great Plains exceed $350 million a year [8]. In Europe, North Africa and West Asia, the most common species is *Cephus pygmaeus* (L.). WSSF larvae cause two types of damage; larval feeding inside the stem reduces the nutrient transfer capability of the plant and weakens the stems. The most severe form of loss is caused by the stems that are girdled and topple to the ground just before harvest. In Morocco and Syria, 40 and 28% of stems cut by WSSF have been reported, respectively [8, 9]. Larvae pass through four or five instars. There is only one generation per year.

20.3.5 Russian Wheat Aphid (Hemiptera: Aphididae)

Russian wheat aphid (RWA), *Diuraphis noxia* (Kurdjumov), with average size of 2 mm, is an important insect pest of wheat in many parts of the world, particularly in dry areas. Its origin is believed to be the Caucasus region, but it has spread widely and is now found on all continents. RWA is light green, elongated spindle-shaped aphid, with distinguishing double tail. Feeding on young wheat leaves causes a number of symptoms including longitudinal chlorotic streaking with a convoluted rolling of the leaf. Rolling of the leaves reduces photosynthetic area and protects aphids from contact insecticides and natural enemies. Yield losses of 20–90% have been reported in different parts of the world [10–12]. Depending on environmental conditions, RWA is reported to have sexual as well as asexual reproduction.

20.3.6 Greenbug (Hemiptera: Aphididae)

The species *Schizaphis graminum* (Rondani), commonly known as greenbug with average adult size of 1.6 mm length, has an uncertain origin, however it is considered of paleartic origin, probably from the Middle East or Central Asia. Its distribution encompasses Asia, Southern Europe, Africa, North and South America. The apterous individuals are light green with dark-tipped siphunculi, and typically with a green longitudinal stripe on their abdomen. *S. graminum* feeds on various genera of Poaceae, e.g. *Agropyron*, *Avena*, *Bromus*, *Dactylis*, *Eleusine*, *Festuca*, *Hordeum*, *Lolium*, *Oryza*, *Panicum*, *Poa*, *Sorghum*, *Triticum* and *Zea*. It is capable of transmitting Barley Yellow Dwarf Virus (BYDV) especially the Schizaphis graminum virus (SGV) strain. Feeding of *S. graminum* on susceptible plants causes chlorosis and necrotic spots at the feeding site.

20.3.7 Bird Cherry-Oat Aphid (Hemiptera: Aphididae)

Commonly known as the bird cherry-oat aphid, *Rhopalosiphum padi (L.),* with a size range of 1–2 mm length, has an origin difficult to trace, since it is currently distributed worldwide. Its sexual phase takes part on various *Prunus* species, e.g. in Europe it overwinters on *Prunus padus* L., and in North America on *P. virginiana* L. Among all aphid species mentioned in this chapter, *R. padi* is the only one able to overwinter on a species other than from the *Poaceae* family. Based on phylogenetic studies using SCAR markers on nuclear DNA, mitochondrial DNA (cyt.b) markers, and tracking life history of aphids, it has been shown that there are two lineages differing in their life cycle: (1) holocyclic, with the sexual phase on the primary host (*P. padus*) and a parthenogenetic phase during summer in Poaceae species; (2) anholocyclic, with only the parthenogenetic phase on grasses; this occurs in places where the winter is mild. The damage caused by this aphid in wheat is not evident to the human eye until plants are seriously damaged, by then plants become yellowish, stunted and most often dead. Even though the economic losses caused by this aphid in the absence of virus are not reported, it can significantly reduce yield by 31% and up to 62% when damage is combined with BYDV infection [13].

20.3.8 English Grain Aphid (Hemiptera: Aphididae)

Sitobion avenae (F.), commonly known as the English grain aphid, probably originates from Europe, and it is currently present in Europe, Northern and Southern Africa, Eastern India and Nepal and North and South America. This species is a yellow-green or reddish-brown aphid, small to medium sized and broadly elongated (1.9–3.5 mm). It has a pale cauda and typically black knees and cornicles, the latter twice as long as the cauda. This aphid species overwinters on Poaceae species where also the sexual cycle occurs, even though aphids can continue reproducing parthenogenetically the whole year. It is a vector of BYDV, particularly the strains *Macrosiphum avenae* virus (MAV) and *Padi avenae* virus (PAV). Similar to *R. padi*, this aphid species does not cause visible symptoms on the wheat plants when feeding, but it can reduce spring wheat yields by 20% at only 300 aphid-days.

20.3.9 Orange Wheat Blossom Midge (Diptera: Cecidomyiidae)

The wheat midge *Sitodiplosis mosellana* (Géhin) is a small (approximately 3 mm long), delicate, mosquito-like orange color fly distributed throughout many wheat-growing regions of the Northern Hemisphere, especially between 42°N and 62°N latitude. From Eurasia – where it is a pest today – it spread to also become a serious pest in North America and China in the 1800s and 1900s, respectively [14–16]. There is a single generation each year. Adult emergence coincides with anthesis. The first two larval instars feed on the developing seed, thereby harming both wheat yield and quality. The seed can be entirely consumed. Infested seeds that are large enough to be harvested exhibit undesirable changes in germination, protein and dough strength. The third instar stays inside the floret until high moisture conditions trigger its departure. Larvae burrow to a depth of a few centimetres and overwinter inside a cocoon. During outbreaks, wheat losses are large. In 1983, an estimated 30 million in Canadian dollars was lost in Saskatchewan. In 2004, an estimated one million tonnes were lost in the United Kingdom [17].

20.4 Mechanisms of Plant Resistance to Wheat Pests

In the middle of the twentieth century, Painter in his classic book Insect Resistance in Crop Plants [18] proposed two types of plant resistance. The first is Antixenosis (also called Non-preference). Here the resistant plant trait interferes with arthropod behavior. Many aspects of behavior contribute to colonization of the plant and existence on the plant, thereafter, including egg-laying by adult females and feeding by larvae. The second is Antibiosis wherein plant traits interfere with the arthropod's physiological processes after it arrives on the plant, including digestion or maturation of eggs. In screening tests, manifestations of plant antixenosis and antibiosis are failure of arthropod survival, growth and/or reproduction, the most extreme form of which is immediate death soon after attack begins.

Plants have physical traits conferring antixenosis and antibiosis – such as trichomes, slippery surfaces, and fortified tissues. However, the most notable plant resistance traits are chemicals. 'Primary plant chemistry' supports basic physiological processes such as growth and reproduction. 'Secondary plant chemistry' supports more specialized functions, including defense against predators and parasites. Some defense chemicals are produced by the plant all the time as 'constitutive defences' whereas others are produced only when they are needed as 'induced defences'. In addition to deployment of induced chemicals in 'direct defence' against arthropods, induced chemicals also are deployed in 'indirect defence' against arthropods by attracting natural enemies of the attacking herbivorous arthropod in order to assist the plant in harming its enemies.

Clearly, plants have evolved traits that allow them to actively resist predators and parasites. It is generally assumed that active resistance traits have a cost for the plant. Resistance traits evolve when the benefit is greater than the cost. Especially prized by agriculturalists are resistance traits that entirely exclude the arthropod from colonizing a particular wheat cultivar. In such cases, we expect strong selection pressure and the possibility that the pest will evolve to overcome the resistance. Now, the resistance trait must be replaced by a different resistance trait. This ongoing cycling of resistance deployment followed by pest or pathogen adaptation is an example of the "arms races" occurring in agriculture.

Painter [18] described an option that reduces selection pressure for the "arms race". Plants have traits that allow them to 'tolerate' the pest. The pest is given a place to live, but the resources it is given are more restricted compared with a genotype lacking the tolerance trait. Traits conferring 'tolerance' have the advantage of less selection pressure but also have the disadvantage of allowing pest populations to persist, albeit at a lower level. Tolerance traits are identified in a screening test in which all plant genotypes are subjected to the same level of attack (usually a low rather than high level). Subsequently, the relative degree of damage exhibited by the various genotypes is scored. Tolerant genotypes are better at growing and reproducing in the presence of the arthropod. The arthropod population grows more slowly on a tolerant versus non-tolerant genotype.

20.5 Genetic Diversity and Gene Mining for Insect Resistance

Wheat genetic diversity, defined as the total number of genetic characteristics present in the *Triticum* species, is the most important factor for wheat improvement in terms of adaptation, yield potential, end-use quality, drought and heat tolerance, resistance to diseases and insect pests. Large number of wheat genetic resources including land races, old cultivars, wild relatives and elite breeding lines are available in the gene banks at CIMMYT and ICARDA and other international and national institutions [19]. However, only a limited amount (about 10%) of the available genetic resources have been utilized for improvement purposes by breeders globally due to (a) gene bank accessions are too obsolete, clumsy and wild with difficulty to breed and even if successful, it may lead into linkage drags, (b) the germplasm is poorly characterized and the available data might not be accessible and match the interest of breeders, (c) enough genetic diversity might be available in the elite breeding lines and varieties. Deployment of effective strategies and tools to undertake gene mining and introgression is highly important to increase the utilization of genetic resources in the wheat breeding programs. Some of these strategies and techniques are indicated in Sections 20.5.1 to 20.5.3.

20.5.1 Focused Identification of Germplasm Strategy (FIGS)

Distribution of genetic resources is a key and core gene bank activity aiming at responding to requests from various users including breeders, researchers, farmers, etc. [20]. When the request does not specify the germplasm and traits sought, a random sample is selected and sent to requesters. Core collections, proposed originally by Brown in 1989 [21], were developed for major crops which include 10% of holdings representing the geographic- characterization- or genetic-based diversity.

To effectively respond to inquiries that directly meet the needs of the users, the focused identification of the germplasm strategy FIGS has been developed at the International Center for Agriculture Research in the Dry Areas (ICARDA) in the last decade. FIGS has become a better alternative to random sampling and the use of core collections since it is specific to each trait and is selecting manageable size subsets with higher probability of finding the desired traits. It is based on finding the relationship between the environmental conditions of collection sites and the traits requested by users.

FIGS uses two approaches: filtering and modeling; both of which select best-bet environments that are likely to have imposed selection pressure for specific traits on *in-situ* populations over time. Developing a FIGS filtering strategy requires deep understanding of the ecology and the optimal conditions of the expression of the trait under study, how these conditions affect the crop, and how this will relate to a selection pressure on an *in-situ* population. The FIGS modeling pathway explores the mathematical relationship between the adaptive trait of interest and the long-term climatic and/or soil characteristics of collection sites. The mathematical conceptual framework of FIGS is based on the paradigm that the trait as a response variable depends on the environment attributes considered as the covariates. The quantification process leads to the generation of *a priori* information, which is used in the prediction of accessions that would carry the desired trait.

Previous success in using FIGS has been reported for example in the identification for sources of resistance to Sunn pest in wheat in Syria and for Russian wheat aphid in bread wheat [22].

Here we represent an example of how a filtering approach was used to select best bet subset for selecting FIGS subset for Sunn pest: 1. Start with all georeferenced landraces for which a suite of monthly agro-climatic data was available from WorldClim (8376 Accessions); 2. Collection sites from a geographic region between latitudes 30° to 45° and longitudes 35°-80° where progressed to the next step to represent areas where Sunn pest has been reported as an historic pest; 3. Sites in China, Pakistan and India were also excluded because there have been only recent reports of Sunn pest in these countries; 4. Accessions collected from sites whose long term average annual rainfall was less than 280 mm per year were excluded as Sunn pest populations are not particularly dense in very arid environments; 5. Accessions from sites that experience long term average minimum monthly temperatures of less than −10 ° C were also excluded as it was hypothesized that areas experiencing particularly harsh winters would not favor high population densities of Sunn pest; 6. Maximizing agroecological diversity which resulted into 534 accessions of which half were from Afghanistan.

The evaluation of this Sunn pest FIGS subset yielded 9 accessions that were resistant to the juvenile stage of the pest (1 from Tajikistan and 8 from Afghanistan), which was an excellent result considering that 1000s had been screened previously without success [4]. This example demonstrates that (1) even a very simple filter, using just monthly temperature and annual rainfall, can be effective at capturing invaluable genotypes, and (2) it is essential to understand something about the biology of the organism in question when designing a filter.

20.5.2 Screening Techniques for Resistance to Wheat Pests

When screening plant materials for resistance to a particular arthropod – whether in the field or the greenhouse – two observations signal the possibility that a particular genotype is resistant. The first is the complete absence of the insect, whereas it is clearly present on other genotypes. The second is reduced presence relative to its greater presence on other genotypes. Conclusions based on such observations are more reliable if a variety of plant genotypes are tested simultaneously. Highly susceptible genotypes must always be included. They act as ‘controls’, providing proof that the absence of the pest from a particular genotype resulted from its ability to resist attack rather than because it escaped attack due to a failure of testing conditions. The screening techniques described below for resistance to Hessian fly, Sunn pest, Cereal leaf beetle, Wheat stem sawfly and Russian wheat aphid are in use at ICARDA [22], whereas those presented for the greenbug, bird cherry-oat aphid and English grain aphid are commonly used at CIMMYT.

20.5.2.1 Hessian Fly

Screening for Hessian fly can be carried out in hotspots in the field under natural infestation but also in the greenhouse. In the field, planting date needs to be adjusted so that 1–2 leaf stage of the crop coincides with the emergence of the flies. For example, in North Africa, a delayed planting date creates strong pest pressure on the tested plants. Evaluation of plant genotypes for resistance is usually made 3–4 weeks after infestation in the greenhouse or when symptoms are clearly seen on the susceptible check. Selection is straight forward, since susceptible plants show stunted growth and a dark green color and contain live larvae, whereas the resistant plants exhibit normal growth and a normal light green color and contain either mostly or only dead first-instar larvae.

20.5.2.2 Sunn Pest

Screening is conducted only in the field under artificial infestation. Test entries are planted under mesh screen cages. Plants are infested at the time of Sunn pest's once yearly migration to wheat fields using insects collected by sweep nets. The evaluation is based on vegetative stage damage either 4 weeks after infestation or when symptoms are clearly visible on the susceptible check. The following rating scale of 1–6 is used to assess shoot and leaf damage (and plant stunting): 1 = no damage and no stunting; 2 = 1–5% damage, with very little stunting; 3 = 6–25% damage with low level of stunting; 4 = 26–50% damage, with moderate level of stunting; 5 = 51–75% damage with high level of stunting, and 6 = >75% damage, with severe stunting.

20.5.2.3 Cereal Leaf Beetle

Because cereal leaf beetle has one generation/year, screening of germplasm is carried out in hotspots in the field under natural infestation. When severe damage is seen on the flag leaf of the susceptible check, the evaluation is conducted using the following rating scale: 1 = no damage, 2 = 10% or less of leaves damaged, 3 = 25% or less of leaves damaged, 4 = 50% or less of leaves damaged, 5 = 75% or less of leaves damaged, 6 = more than 75% of leaves damaged, including the flag leaf.

20.5.2.4 Wheat Stem Sawfly

Wheat stem saw fly produces one generation/year. Screening of germplasm for resistance to this pest is mostly carried out in hotspots in the field under natural infestation. At the end of the season, just prior to harvest, evaluation for resistance is based on the % stems cut by larvae: >30% = susceptible, 20–30% = moderately susceptible, <10% = moderately resistant, <5% = resistant.

20.5.2.5 Russian Wheat Aphid

Screening for Russian wheat aphid is carried out in hotspots in the field under natural and/or artificial infestation but also in the greenhouse. Evaluation is made when symptoms of leaf rolling and leaf chlorosis are clearly visible on susceptible checks using a 1–3 scale for leaf rolling (LR), where: 1 = no rolling, 2 = trapping or curling in one or more leaves, and 3 = rolling in one or more leaves. For leaf chlorosis (LC) a 1–6 scale is used where: 1 = no LC, 2 = <33% of leaf area with LC, 3 = 33–66% area with LC, 4 = >66% area with LC, 5 = necrosis in at least one leaf, and 6 = plant death [23].

20.5.2.6 Greenbug

Because of the symptoms caused by *S. graminum* it is possible to perform massive screenings, allowing the identification of resistant germplasm in short spans (10–14 days). Protocols consist of sowing row or hill plots of eight to ten seeds in flats; 3 days after emergence plants are infested by placing infested leaves on the plots with an average density of four to five aphids per plant; scores of symptoms in percent of chlorosis are taken 10–14 days after infestation, or using a 0–9 damage scale where: 0 = No damage and 9 = dead. However, more quantitative and eye-independent measurements, is the evaluation of chlorophyll content, which has been successfully used in wheat to identify resistance sources and map chromosomic regions associated with the resistance [24].

20.5.2.7 Bird Cherry-Oat Aphid & English Grain Aphid

Evaluating resistance to these two aphid species is more challenging, since none of these cause visible symptoms on the plants. One option is to conduct the typical life table assessments, where the intrinsic rate of increase is calculated, however, this is time consuming and the number of plant materials that can be evaluated is limited. Another option is to determine the aphid growth, this allows a somewhat larger number of genotypes to be evaluated. One more option is to assess the biomass loss of the seedlings in an infested vs. non-infested setup. There is one additional complication, in the case of the EGA it is fundamental to asses the germplasm at the adequate phenological stage, since evaluations at other stages can result in false positive results.

20.5.2.8 Orange Wheat Blossom Midge

Field screening methods have enabled resistance scoring of hundreds or even thousands of genotypes in a single season. Two to three weeks after egg-laying occurs, an evaluator threshes a wheat spike (5 per plot), noting the presence of the bright orange mature larva. Genotypes that exclude larvae or support significantly fewer larvae compared to susceptible controls are classified as resistant. Genotypes can be misclassified as resistant if planted too early or too late, making the spike either no longer attractive to the egg-laying female or not suitable for larval colonization of the seed embryo. Bad weather can also prevent infestation. Multiple planting dates help reduce these problems but restrict the number of genotypes that can be screened each season. Screening in the greenhouse does not have these problems but requires establishment of a laboratory colony, each generation of which requires a 5-month long period of obligatory diapause in the cold.

20.5.3 Identification and Introgression of Insect Resistant Genes

Using the FIGS approach and the different screening protocols of screening for insect resistance both in the field under hot spot locations and in the greenhouse using artificial inoculation, important *Resistance* (*R*) genes have been identified and mapped for each of the important wheat insect pests including the Hessian fly, Wheat midge, Greenbug, Russian wheat aphid and Wheat curl mite. According to Harris et al. [25], out of the total 479 R genes reported in wheat, only 69 R genes are targeted for insects and mites, mainly for Hessian fly (37 genes), Russian wheat aphid (11 genes) and Greenbug (15 genes). Most of the resistance genes for Hessian fly were identified from *Triticum aestivum* accessions such as Grant, Patterson, 86981RC1-10-3, 8268G1-19-49, KS89WGRC3 (C3), and KS89WGRC6 (C6). Similarly, the majority of the Russian wheat aphid genes were identified from *Triticum aestivum* genotypes (PI137739, PI262660, PI 294994, PI 372129, PI 243781). *Aegilops tauschii* accessions have been identified as excellent sources of resistance for Greenbug, Russian wheat aphid and Hessian fly [26–28]. Rye (*Secale cereale*) has been reported as the source of *H25* for Hessian fly, *Gb2* and *Gb6* for Greenbug while *Aegilops triuncialis* has been reported as the source of H30 gene of Hessian resistance.

Because of the co-evolution between wheat and insects, stacking of major R genes is very important for the development of durable resistance. This is mainly feasible for Hessian fly, Greenbug, Russian wheat aphid and the Wheat curl mite since there are R genes clustered around the same chromosome intervals. For example, for Hessian fly, there are 15 genes reported on the short arm of chromosome 1A (*H3, H5, H6, H9, H10, H11, H12, H14, H15, H16, H17, H19, H28, H29* and *Hdic)*; three genes on the long arm of chromosome 3D (*H24, H26, H32*) and three genes on the short arm of chromosome 6D (*H13, H23,* H_{WGRC4}). Similarly, for Russian Wheat Aphid six *Dn* genes are clustered on the short arm of chromosome 7D (*Dn1, Dn2, Dn5, Dn6, Dn8* and *Dnx*) (Dweikat et al. 1997) and for Greenbug resistance 8 *Gb* genes are clustered on the long arm of chromosome 7D (*Gbx1, Gba, Gbb, Gbc, Gbd, Gbz, Gb3* and *Gbx2*) (Zhu et al. 2005). Some of these genes such as H9 and

H10; H26 and H32; *Dn1*, *Dn2*, *Dn5*, *Dn6* and *Dnx*; *Gbz* and *Gb3* are tightly linked and hence they can be easily introgressed simultaneously during the gene pyramiding process.

The resistance sources from wheat relatives and land races do not have all the desired traits to be a variety by themselves. They can only serve as gene sources for traits of interest such as insect resistance, drought and heat tolerance, disease resistance, etc. Introgression of such genes from wild relatives into common wheat is very difficult and requires efficient introgression techniques and approaches (for more details see Chap. 18). Though there are successful natural gene introgressions as exemplified by wheat–rye translocations of 1BL.1RS and 1AL.1RS, which arose spontaneously from centromeric breakage and reunion, gene introgression/transfer in pre-breeding programs can be carried out using gene transfer through hybridization and chromosome- mediated gene transfer approaches or through direct gene transfer using molecular approaches. The most successful and highly used gene introgression techniques is the development of primary synthetic wheats (2n =6x = 42, AABBDD) which is an amphiploidy developed by crossing the *T. turgidum* spp. *durum* (2n = 4x = 28, BBAA) with *Ae. tauschii* (2n = 2x = 14, DD) and chromosome doubling of the F1 through colchicine treatment [29]. The primary synthetic wheats have served as a bridge to transfer important genes such as resistance to Hessian fly, aphids, Sunn pest and many other important genes for resistance to abiotic and biotic stresses [22–24, 30, 31]. Recently, screening of synthetic wheats for resistance to HF and Sunn pest has resulted in the identification three synthetic hexaploid wheat lines possessing resistance to both Moroccan Hessian fly biotype and Syrian Sunn pest [32].

20.6 Breeding for Insect Resistance

The main objective of any breeding programme is to develop high yielding, better quality and adapted varieties with resistance to the major abiotic and biotic stresses prevailing in the target region. Breeding for insect resistance should be carried out in combination with other important traits targeting the regions where the insect pest is economically important. The wheat programs at CIMMYT and ICARDA undertake intensive characterization of parents for different traits such as yield potential, disease (root and foliar) resistance, heat and drought tolerance, insect resistance (Hessian fly, Sunn pest and aphids) and better nutritional quality. Once the progenitors are characterized the breeding programs assemble crossing blocks targeting wheat growing regions in developing economies. High yielding and adapted hall mark wheat cultivars representing the major-agro-ecologies, synthetic derived hexaploid wheats, and elite lines are included in the different crossing blocks. Simple, three-way and back crosses are carried out commonly with the application of diagnostic markers for gene pyramiding in the F2, F1top, and BC1 F1 populations [19, 33]. Selection of the segregating generation for different traits from F2 to F4 is carried out using the selected bulk or modified pedigree selection schemes as indicated (Fig. 20.3).

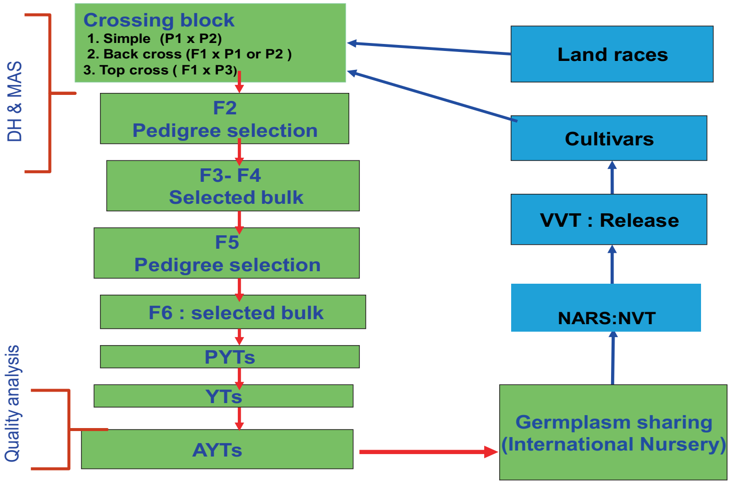

Fig. 20.3 Germplasm development and distribution scheme for Hessian Fly and Sunn Pest resistance at ICARDA; *P* parent, *F* Filial generation, *DH* Doubled Haploids, *MAS* Marker Assisted Selection, *PYTs* Preliminary Yield Trials, *YTs* Yield Trials, *AYTs* Advanced Yield Trials, *NVT* National Variety Trial, *VVT* Variety Verification Trial

In addition to the scheme indicated in Fig. 20.3, ICARDA has developed a modified speed breeding for elite x elite crosses whereby we manage crosses and F1s in the greenhouse and segregating generations and head-rows in the field at Merchouch in Morocco using summer x winter shuttle approach. Elite genotypes at F7 stage are evaluated in hotspot locations at Jemmaa Shaim in Morocco for Hessian fly and at Terbol station in Lebanon for Sunn pest resistance following the screening techniques indicated earlier in this chapter. The elite genotypes are also evaluated across key locations for yellow and stem rusts resistance at Kulumsa (Ethiopia) and Izmir (Turkey), for heat tolerance at Wadmedani (Sudan) and for root diseases, drought tolerance at Merchouch and Sid Al Aydi stations in Morocco. Elite genotypes with high yield potential, yellow rust resistance, drought and heat tolerance with 100% resistance to the Moroccan Hessian fly biotype have been identified and distributed to national programs in the CWANA region through ICARDA's international nursery distribution system for direct release and parentage purposes [19].

Similarly, breeding programs in the USA have developed resistant varieties for the major insects such as Hessian fly, Russian wheat aphid, Greenbug, and Wheat stem saw fly. More than 60 Hessian fly resistant wheat varieties have been released in the USA between 1950 and 1983 and less than 1% yield loss have been reported in areas where resistant cultivars have been deployed [34]. Resistance conferred by the *Sm1* gene has revolutionized management of Wheat midge [35]. Discovered by Canadian researchers in 1996, *Sm1* is now deployed in many parts of the world. Larvae die without causing damage to developing seeds. To ensure long-term durability of *Sm1*, the Canadian Wheat Board took the unusual step of requiring *Sm1* be deployed in a 90:10% mixture of resistant to susceptible seeds.

20.7 Summary

Genetic diversity for resistance to biotic and abiotic stresses is the backbone for the success of any breeding program. Studies to-date have shown the availability of enough genetic diversity in the wheat genetic resources (land races, wild relatives, cultivars, etc.) for resistance to the most economically important insect pests such as Hessian fly, Russian wheat aphid, Greenbug and Sunn pest. Many R genes – including 37 genes for Hessian fly, 11 genes for Russian wheat aphid and 15 genes for Greenbug – have been identified from these genetic resources. Some of these genes have been deployed singly or in combination in the breeding programs to develop high yielding varieties with resistance to insects. Gene pyramiding using marker assisted selection is important to stack two or more R genes in an adapted cultivar in order to increase the durability of insect resistance. Breeding for tolerance traits would exert less selection pressure on insect pests to evolve the ability to overcome the deployed trait. It is also important to develop and deploy resistant varieties in a given agro-ecology instead of using a given variety across a large mega-environment along with integrated pest management options in order to slow down the development and spread of virulent biotypes of the insect pests.

20.8 Review Questions

1. Describe the most important insect pests of wheat.
2. What are the mechanisms of insect resistance?
3. Explain the most common sources for insect resistance and the most efficient and widely used strategies for gene introgression from wild relatives of wheat.
4. Explain the breeding methods to develop and deploy high yielding varieties with Hessian fly resistance.

20.9 Key Concepts

Identification, development and deployment of insect resistant wheat varieties in integrated pest management scheme (IPM) is the most economical, socially feasible and environment friendly approach.

20.10 Conclusions

Wheat genetic resources are reservoirs for different genes including for resistance to insects. Identification and introgression of these insect resistant genes into adapted cultivars using both classical and molecular approaches is key for successful development of high yielding and widely adapted wheat varieties with resistance to major insect pests.

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