Chapter 10
Sustainable Pest Management in Rainfed Farming Systems

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Abstract Insect pests are estimated to cause losses of 16% to world attainable crop production with post-harvest losses another 10%, in spite of widespread use of pesticides. Losses due to pests have been estimated for key rainfed crops in different regions of the world. Pest species attack every phenological stage of crop growth; sometimes they are the same species and sometimes different. No one tool can be used to successfully control a pest; integrated pest management principles have been widely adopted and include determining the economic threshold at which control is cost effective. Chemical control is widely used but excessive use can cause resistance in the insect and adverse environmental effects. The enhancement of use of natural enemies of pest insects, and use of crop cultivars resistant to the insects are both very important. Crop management practices used to reduce the impact of pests include crop rotations, intercropping, sowing rates, sowing time and soil tillage. Management of pests requires growers to understand the interactions between the pests and crops in their regions and to use the most appropriate tools to reduce the potential damage. While no one system would be applicable to a crop or to a pest in all rainfed farming systems, some general principles are relevant across regions.

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10.1 Introduction

Global productivity of all crops has increased five-fold over the past five decades. High-yielding varieties, irrigation, fertilisers and pesticides have delivered rapid economic growth and also reduced poverty (Lenne 2000) in countries with access to these resources. However, the expanding human population and degradation from more intensive production has resulted in a decrease in per capita availability of arable land (Dyson 1999). While developed countries have adequate food supplies, many developing countries, particularly in Africa, do not have adequate food, and many people suffer from malnutrition (Weber 1999). One practical way of increasing crop production is to minimise the losses from pests. Oerke et al. (1994) estimated that more than 42% of the total attainable production for eight major crops is lost due to pests – 16% due to insects, 13% due to diseases and 13% due to weeds. Post-harvest losses in grains are a further 10%. The total value of losses due to all pests (the difference between attainable production and actual production) is estimated to be $578 billion annually, and this occurs despite the application of pesticides valued at $30 billion annually (Crop Protection Compendium 2004).

10.2 Losses in Value of Production and in Yields Due to Pests Across Regions and Crops

Losses in value of attainable production due to animal pests, pathogens and weeds vary regionally; in Africa and Asia losses are estimated at around 50%, in Oceania 36%, and in North America and Europe at around 30% (Oerke 1994). The average dollar value of the economic losses caused by animal pests is 12% in the five crops for the regions considered to have substantial rainfed agriculture and for which data are available (Table 10.1). When the data are expressed as yields (kg/ha), the difference in actual and potential yield losses are similar for wheat, barley and soybean, but for maize and oilseed rape, potential losses due to insects are far greater than the actual losses; and pests are a greater threat to production in maize and oilseed rape (Table 10.2). Grain stored after harvest is infested by pests unless protected. Chickpea storage losses from the bruchids, *Callosobruchus chinensis* and *C. maculatus,* can range from 7% to 70% in Syria, and from 24% to 100% in Jordan (Clement et al. 1999). There are clearly substantial benefits to be obtained from maintaining and improving pest management in rainfed farming systems.

Table 10.1 Actual crop losses caused by animal pests (invertebrates and vertebrates) in relation to actual crop production (arranged by regions) (Reproduced from the Crop Protection Compendium (2004). ©CAB International, Wallingford, UK)

	Value ($US M) of actual production and losses from animal pests									
	Wheat		Barley		Maize		Soybean		Oilseed rape	
Region[a]	Production	Losses	Production	Losses	Production	Losses	Production	Losses	Production	Losses
North America	7,958	1,000	1,249	89	23,888	1,967	11,977	1,130	1,016	120
Southern South America	2,246	783	92	7	5,625	914	12,549	1,538	14	1
North Africa	1,426	178	217	31	646	80	2	0	14	1
Southern Africa	246	28	12	1	962	206	44	6	0	
Southern Europe	1,595	137	742	62	1,749	160	117	3	7	0
European CIS	6,048	1,019	2,146	230	577	119	74	12	46	7
Near East	4,256	542	878	92	384	60	32	4	0	
South Asia	9,889	1,002	119	12	1,533	474	967	240	823	165
Asiatic CIS	2,351	387	235	25	126	27	2	0	1	0
East Asia	9,809	934	301	25	11,299	1,440	2,736	425	2,006	306
Oceania	1,989	264	463	54	56	6	12	0	236	35
Total	47,714	6,274	6,454	628	46,845	5,453	28,512	3,358	4,163	635

[a] See end-note for countries in regions

Table 10.2 Actual and potential crop losses due to animal pests (invertebrates and vertebrates) in relation to actual and potential crop yields across regions and crops (Reproduced from the Crop Protection Compendium (2004). ©CAB International, Wallingford, UK)

		Actual production (kg/ha)		Attainable production (kg/ha)	
Crop	Region	Yield	Loss	Attainable yield	Potential loss
Wheat	Oceania	1,629	216	2,494	238
Barley	European CIS	2,076	223	3,219	213
Maize	North America	8,397	691	10,769	1,688
Soybean	South America	2,677	328	3,628	353
Oilseed rape	East Asia	1,494	228	2,160	402

10.3 Insect Pest Damage

Although damage is the result of insect feeding, it may appear some time after the feeding has occurred. Larvae of the scarab, *Sericesthis nigrolineata*, feed on the roots of perennial ryegrass (*Lolium perenne*), but leaf production is reduced only when the plants are also grazed. Despite feeding by high densities of larvae, patches of dead grass are not seen until the plants are water-stressed – which may be long after the larvae have fed on the roots (Ridsdill-Smith 1977).

Insects feeding on leaves may cause plants to produce fewer pods; yellow lupins (*Lupinus luteus*) attacked by the redlegged earth mites, *Halotydeus destructor,* at the seedling stage produce smaller mature plants with a lower seed yield (Liu et al. 2000). However, some plants can compensate for insect feeding by producing more pods (Tingey 1981); chickpea and pigeonpea produce extra pods to replace those damaged by the cotton bollworm/legume pod borer, *Helicoverpa armigera*, feeding (Srivastava and Srivastava 1989). Strategies to reduce damage require an understanding of the plant–insect interactions.

10.4 Regional Differences in Pests Causing Damage

Every phenological stage of the crop is attacked by a suite of pest species which are different in each region (Tables 10.3–10.7). Pests of crop seedlings include mites, wireworms, weevils and cutworms. Several noctuids and leaf miners feed on leaves; pyralids, Hessian fly, sorghum shoot fly and aphids feed on shoots whereas wireworms, termites, and larvae of scarab beetles and weevils are root feeders. Pests of green pods/grain include budworm, pod borers, pod-sucking bugs, sorghum midge and pea weevil, while the post-harvest pests are mainly beetles, in particular *Callosobruchus, Tribolium, Rhizopertha, Trogoderma*.

An insect species may become a pest in a region as a result of the introduction of new crops or plants. In Australia, several species have become pests of pastures

Table 10.3 Some economically important insect pests of rainfed crops in Australia

Plant stage	Common name	Latin name	Plant attacked
Seedlings	Redlegged earth mite	*Halotydeus destructor*	Pasture legumes (Pavri 2007) Canola (Berlandier and Baker 2007) Cereals (Hopkins and McDonald 2007)
Leaves and stems	Common armyworm	*Leucania convecta*	Cereals (Hopkins and McDonald 2007)
	Diamondback moth	*Plutella xylostella*	Cruciferous crops (Berlandier and Baker 2007)
Roots	Redheaded pasture cockchafer	*Adoryphorus couloni*	Pasture grasses (Pavri and Young 2007)
	Sitona weevil	*Sitona discoideus*	Pasture legumes (Pavri 2007)
Green pods and seeds	Corn earworm and native budworm	*Helicoverpa armigera* and *H. punctigera*	Grain legumes and cereals (Miles et al. 2007; Fitt 1989)
Dry post-harvest seeds	Lesser grain borer	*Rhyzopertha dominica*	Stored grain and cereal products (Emery 2000)
	Rust red flour beetle	*Tribolium castaneum*	Cereal products (Emery 2000)

Table 10.4 Some economically important insect pests of rainfed crops in North America

Plant stage	Common name	Latin name	Plant attacked
Seedlings	Wireworms	*Ctenicera destructor*	Wheat (Oerke 1994)
Leaves and stems	Fall armyworm	*Spodoptera frugiperda*	Maize (Oerke 1994)
	Corn earworm	*Helicoverpa zea*	Cereals (Oerke 1994)
	Greenbug	*Schizaphis graminum*	Sorghum (Smith et al. 1999)
Roots	Corn rootworms	*Diabrotica* spp.	Maize (Oerke 1994)
Green pods and seeds	Hessian fly	*Mayetiola destructor*	Wheat (Smith et al. 1999)
	Pea weevil	*Bruchus pisorum*	Peas (Clement et al. 2000)
	Sorghum midge	*Stenodiplosis sorghicola*	Sorghum (Sharma 1993)
Dry post-harvest seeds	Bruchids	*Callosobruchus* spp.	Grain legumes (Sharma et al. 2007a)

following the introduction of exotic grasses and legumes and changes in management (Panetta et al. 1992). Host identification by post-harvest grain pests occurs with the flowers. For example, *Bruchus lentis* requires pollen and nectar of the lentil, *B. dentipes* requires the pollen and nectar of the faba bean, whereas *B. pisorum* produces eggs most readily when fed on pea pollen (Clement et al. 1999).

Table 10.5 Some economically important insect pests of rainfed crops in West Asia

Plant stage	Common name	Latin name	Plant attacked
Seedlings	Sitona weevil	*Sitona crinitus*	Lentils (Beniwal et al. 1993)
Leaves and stems	Cereal bug	*Aelia rostrata*	Cereals (Oerke 1994)
	Leaf miner	*Liriomyza cicerina*	Chickpeas (Clement et al. 1999)
Roots	Sitona weevil	*Sitona lineatus*	Faba bean, Peas (Clement et al. 2000)
Green pods and seeds	Pea weevil	*Bruchus pisorum*	Field peas (Clement et al. 2000)
		B. dentipes	Faba bean (Clement et al. 1999)
Dry post-harvest seeds	Bruchids	*Callosobruchus chinensis* *C. maculatus*	Grain legumes (Clement et al. 1999)

Table 10.6 Some economically important insect pests of rainfed crops in South Asia

Plant stage	Common name	Latin name	Plant attacked
Seedlings	False wireworms	*Gonocephalum* spp.	Chickpea (Sharma et al. 2007a)
	Sorghum shoot fly	*Atherigona soccata*	Sorghum (Sharma 1993)
Leaves and stems	Stalk and stem borers	*Chilo partellus*	Maize (Sharma and Ortiz 2002)
		Sesamia inferens	Sorghum (Sharma 1993)
	Oriental armyworm	*Mythimna separata*	Cereals (Sharma 1993)
Roots	Termites	*Odontotermes obesus* *Microtermes* sp.	Chickpea (Sharma et al. 2007a)
Green pods and seeds	Pod borer	*Helicoverpa armigera*	Chickpea, pigeonpea (Clement et al. 2000; Sharma and Ortiz 2002)
	Sorghum midge	*Stenodiplosis sorghicola*	Sorghum (Sharma 1993)
Dry post-harvest seeds	Bruchids	*Callosobruchus chinensis* *C. maculatus*	Grain legumes (Clement et al. 2000)

Seasonal climatic factors also influence the occurrence and abundance of pests in a region. Some have resting stages to overcome adverse seasonal conditions. The mite, *H. destructor,* is winter-active and undergoes a summer diapause to avoid a hot dry summer (Ridsdill-Smith et al. 2005), whereas *H. armigera* is summer-active and has a winter diapause to avoid a cold wet winter (Fitt 1989). Species present in a region may attack only one of the crops present, or may cause damage only at certain times of the year. Knowledge of the biology of individual species is required for planning appropriate control measures.

Table 10.7 Some economically important insect pests of rainfed crops in East and southern Africa

Plant stage	Common name	Latin name	Plant attacked
Seedlings	Cutworms	*Agrotis* spp.	Most crops (Van den Berg and Drinkwater 1999)
	Redlegged earth mite	*Halotydeus destructor*	Pasture legumes and cereals (Prinsloo et al. 1999)
Leaves and stems	Maize stalk borer	*Busseola fusca*	Maize (Van den Berg and Drinkwater 1999)
	Russian wheat aphid	*Diuraphis noxia*	Cereals (Prinsloo et al. 1999)
Roots	Termites	*Microtermes* spp.	Annecke and Moran (1982)
	Black maize beetle	*Heteronychus arator*	Prinsloo et al. (1999)
Green pods and seeds	African bollworm	*Helicoverpa armigera*	Rainfed crops (Prinsloo et al. 1999)
	Sorghum midge	*Stenodiplosus sorghicola*	Prinsloo et al. (1999)
Dry post harvest seeds	Maize beetles	*Sitophilus* spp.	Maize (Oerke 1994)

10.5 Integrated Pest Management

It is seldom that a single tool can be used to successfully control a pest. More commonly, growers need to apply a combination of tools including chemical control, biological control and cultural control. The most effective control is achieved with chemical insecticides. However, in many cases, the use of chemicals is not economically viable, and the repeated use of the same chemical year after year is not biologically sustainable because it leads to non-target environmental impacts and development of resistance to chemical pesticides in the pest population. The approach of using multiple tactics to manage pests is called *Integrated Pest Management* (IPM). 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" (Kogan 1998). Chemical control and biological control are principal tools in the IPM toolbox that can be integrated into a sustainable production system. However, many interactions occur between the individual elements of an integrated control strategy, and this complexity, combined with the difficulty of correctly applying each element, has been a barrier to the adoption of integrated strategies by farmers (Orr 2003; Rodriguez and Neimeyer 2005).

10.6 Economic Thresholds

The economic threshold is the pest density at which a control tactic should be applied in order to both minimise yield losses and cover the cost of control. Economic thresholds, where controls are applied only when the pest population exceeds the threshold, are considered the keystone for implementing IPM strategies (Pedigo and Rice 2006). Effective use of thresholds requires active monitoring of pest populations. Monitoring is achieved mostly by visual observation, but also by counting the numbers of insects caught using methods such as a sweep nets, light traps, or traps baited with pheromones specific to the pest.

Economic thresholds vary with the species of insect and the crop. In Australia, control of pea weevil, *B. pisorum*, in field peas is proposed when there is more than one adult beetle per 10 sweeps; the control of native budworm, *Helicoverpa punctigera*, in field peas when there are more than 1–2 larvae per 10 sweeps, and the control of native budworm in chickpeas when there are more than 2–5 larvae per 10 sweeps (Miles et al. 2007). In India, economic injury levels are judged by visual assessments when there are 0.1–0.2 adults per panicle for sorghum midge (*Stenodiplosis sorghicola*) on sorghum (Sharma et al. 1993), or one larva per plant for the pod borer (*H. armigera*) on chickpea (Wightman et al. 1995).

The economic threshold will vary with phenology of the plant. Thus, the economic threshold for diamondback moth (*Plutella xylostella*) in Western Australian canola is 50 larvae per 10 sweeps in the pre-flowering plants, 100 larvae per 10 sweeps in mid-flowering plants, and 200 larvae per 10 sweeps in plants with mature pods (Micic 2005).

The threshold will also change with the level of resistance of a cultivar. The economic threshold of sorghum midge can vary by a factor of 10 between susceptible and resistant sorghum cultivars (Sharma 1993). Economic thresholds usually involve only a single pest in a system and do not consider the synergistic or antagonistic interactions between several pest species and with other pest organisms such as weeds or plant pathogens. In canola grown in western Canada, early weed removal is the promoted practice, but this increases the damage to canola caused by root maggots, which increases the need for insecticide application (Dosdall et al. 2003). Weekly scouting of wheat is advised in Australia since different pests attack the crop at different development stages (Emery 2000). Economic thresholds are determined using the direct costs of control, but they should also include non-target effects of pesticides on the environment, on human health, and on beneficial insects – which are harder to assess (Higley and Pedigo 1993). Although economic thresholds are not easy to use in practice, they do provide a useful guide to help growers make cost effective decisions about pest management and to integrate multiple tactics for control into the production system.

10.7 Chemical Control

The principle element of insect pest control is the use of chemicals, the main groups being the organophosphates, carbamates, and the synthetic pyrethroids. As chemicals are relatively easy to apply and the results usually immediate, the use of pesticides (in the widest sense) has increased ten-fold since 1970 (Dehne and Schonbeck 1999). It has been estimated that more than three-quarters of the world use of pesticides is in North America, Western Europe and Asia, but less than one third of all cropland in the world is treated with a pesticide (Dehne and Schonbeck 1999). In Australia, nearly all the sorghum crop, about 80% of canola and field peas, half of chickpea and lupins, and 16% of wheat and barley crops are treated with pesticides (Ridsdill-Smith 2002).

Forecasting and modelling have been used to improve the decisions on timing and need for chemical control of pests in crops (Apel et al. 1999; Clement et al. 2000). A model can optimise application time; for example, from the prediction of the onset of summer diapause in redlegged earth mite, a single spray can prevent development of the over-summering generation and provides good control of mites in the following autumn – 8 months later (Ridsdill-Smith et al. 2005). A relatively simple simulation model of *H. armigera* on pigeonpea, based on the flowering phenology of the crop, has been developed to optimise insecticide use (Holt et al. 1990). Nietschke et al. (2007) have developed a database of temperature development requirements for 500 insect species for use in decision support systems in pest management.

No insects are permitted in grain exported from Australia, and this is maintained by inspection and fumigation. Virtually all grain that is exported is therefore treated with insecticides, and restrictions are in place to help manage pesticide residues in grain and to avoid the development of resistance to insecticides (Emery 2000).

While repeated applications of pesticides may kill the pests effectively, they can also leave harmful residues in the food, cause adverse effects to non-target organisms and the environment, and may lead to the evolution of resistance in pest populations. Once a resistance gene is present, it increases in frequency in the population every time that pesticide is applied to the progeny of the same insect species, even if the insects are on different crops grown in rotation. Resistance to one insecticide may also confer cross-resistance to other insecticides, particularly where these insecticides have similar modes of action; i.e. they inhibit insect biochemistry in a similar way. Following repeated applications over several years, if there is a period of several generations when the insecticide is not applied to the progeny of the resistant pest, then the frequency of resistant alleles in the population will be expected to fall, and resistance will not continue to develop. Approximately 500 arthropod species have developed resistance to at least one pesticide, and some key pest species are resistant to nearly all of them (Devine and Denholm 2003). The likelihood of developing insecticide resistance in a pest population is reduced if compounds with different modes of action are used alternately to control pests, and if repeated use in the same field of a particular insecticide is avoided.

Many plants are naturally resistant to insect pests because they possess chemical defences to attack from insect pests. In India, natural plant products, such as the leaves of the neem tree (*Azadirachta indica*), are used in on-farm grain stores to reduce damage by insect pests (Shanker and Parmar 1999). Some of these compounds have been identified as potential insecticides. The insecticide pyrethrin, for example, is derived from plants of the genus *Chrysanthemum*. Although a number of plant products, such as azidirachtin from neem, and compounds from the custard apple (*Annona reticulata*), are considered safer than conventional insecticides

(Shanker and Parmar 1999), the chemical structures of these compounds are very complex, and it is not feasible or cost-effective to synthesise and produce them on a commercial scale.

10.8 Biological Control

A large number of parasites, predators, bacteria, fungi and viruses reduce populations of insect pests under natural conditions (King and Coleman 1989), and farming practices can be developed that will enhance their abundance and activity. The most obvious method is to reduce rates of insecticides applied or to use selective insecticides that conserve the natural enemies. Booth et al. (2007) observed that lacewings are less sensitive to insecticides than are their prey, the bird cherry-oat aphid, and reduced insecticide rates are therefore quite effective against the aphids, but kill few lacewings. Similarly, spinosad (spinosyn A and spinosyn B) has less affect on *Harmonia axyridis*, a ladybird beetle and natural enemy of soybean aphid (*Aphis glycine*), than indoxacarb (Galvan et al. 2006).

Enhancing the spaces between crop rows or around the crops provides refuges for natural enemies. Many cereal fields contain habitats for spiders, ants, beetles and other predatory invertebrates that feed upon cereal aphids (Brewer and Elliott 2004). Predators can effectively reduce early populations of soybean aphid (Costamagna and Landis 2006). Weeds within a crop may act as a niche for natural enemies of the pests (Sharma and Ortiz 2002); sunflower, niger (*Guizotia abyssinica*) and canola act as refuge plants that support the predatory assassin bug, *Pristhesancus plagipennis,* in annual field crops in Australia (Grundy and Maelzer 2003). Many parasitoids and predators have prolonged longevity and fecundity when provided with access to carbohydrate-rich foods such as floral and extra-floral nectar. Provision of flowering plants in hedge plantings or uncultivated areas has also been suggested as a means of conserving natural enemies. However, Prasad and Snyder (2006) argue that because many predators are generalists, they will feed on both pest and non-pest species in a crop which may reduce the effectiveness of other predators in controlling the target pest species. Therefore, while it is evident that provision of supplemental foods is of benefit to natural enemies, it is important that such approaches are evaluated in each system to determine the overall benefits for pest management. *Augmentative biological control* can be used for pest suppression; a natural enemy is reared in an insectary and then released into the crop to control pests. Augmentative release of *Trissolcus basalis*, a parasitic wasp, reduced stinkbugs (*Nezara viridula*) by 54% in soybean in Brazil (Correa-Ferreira and Moscardi 1996), but this has been less effective in Australia (Knight and Gurr 2007). However, augmentative releases of the assassin bug (*P. plagipennis*) reduce the numbers of *Helicoverpa* spp. and mirids in cotton and soybean crops in Australia (Grundy and Maelzer 2003). The egg parasitoids, *Trichogramma* spp. and the chrysopid, *Chrysoperla carnea,* have been recommended for biological control of *H. armigera* in India (Sharma et al. 2007b). *Classical biological control* occurs when living organisms are introduced from another country and released in a new environment to suppress pest densities, typically in regions the pest has invaded without its natural enemies. In Australia, the spotted alfalfa aphid (*Therioaphis trifolii*) appeared in 1977 and devastated lucerne crops. Three exotic wasp parasitoids (biological control agents) were introduced and, within 6 years, one of these (*Trioxys complanatus*) had successfully controlled the aphid (Hughes et al. 1987). This provided time for the plant breeders to develop and plant aphid-resistant lucerne varieties. Plant resistance has now become the key factor in controlling the aphids.

10.9 Host Plant Resistance

There are many varieties of crop plants being grown on farms that are resistant to insect pests. These varieties can play a major role in integrated pest management (Smith 1989; Sharma and Ortiz 2002), and investment in breeding plants for pest resistance could provide a larger benefit than investment in insecticide research (Smith et al. 1999). In spite of this, the adoption of insect-resistant cultivars has not been as rapid as adoption of disease-resistant cultivars (Muehlbauer and Kaiser 1994), partly a result of the relative ease of insect control with insecticides. Progress in developing insect-resistant cultivars has also been slow because of the difficulties of conducting large-scale resistance screening effectively. However, the total value of genetic resistance in wheat, to greenbug (*S. graminum)*, Hessian fly (*M. destructor*) and the wheat curl mite (*Aceria tosichella*) that transmits wheat streak mosaic virus in the USA, has been estimated to be $US250 million annually (Smith et al. 1999). Host-plant resistance in sorghum has been effective in managing sorghum midge (*S. sorghicola*), greenbug (*S. graminum*), mites (*Oligonychus* spp.) and head caterpillar (*H. armigera*), but needs to be supplemented with other methods for controlling shoot fly (*A.soccata*), stem borers (*C. partellus*), armyworm (*M. separata*) and head bug (*Calocoris angustatus*) (Sharma 1993). Partial resistance in sorghum to greenbug (*S. graminum*) has delivered a benefit/cost ratio of 13:1 in terms of reduced insecticide use, and to sorghum midge a benefit/cost ratio of 9.9:1 (Teetes et al. 1999). New sources of resistance to pests are being investigated in several wild relatives of crop plants (Clement et al. 1999; Sharma et al. 2005).

The benefits of plant resistance are greater when deployed with other control tactics. Sorghum varieties with low to moderate levels of resistance against a range of pests can assist pest suppression over time by reducing pest density, assisting in control with natural enemies, and reducing the number of insecticide treatments needed (Sharma et al. 1993). For example, partial plant resistance that reduces the rate of increase of sorghum midge can allow natural enemies to have a greater impact in controlling the midge (Sharma 1994). Higher levels of parasitisation of stem borer (*C. partellus)* by *Cotesia flavipes* have been recorded on stem borer-resistant genotypes of sorghum than on susceptible ones (Duale and Nwanze 1997).

Resistance can be developed transgenically by adding exotic genes from novel sources into crop plants through genetic engineering. Most transgenic crops with resistance to insect pests contain genes from only one species, *Bacillus thuringiensis*. Since the mid-1980s, there has been a rapid growth in the area planted with transgenic crops in USA, Australia, China and India. The global area planted to transgenic crops in 2006 was approximately 100 million hectares (ISAAA 2006). Continuing investigations are underway to broaden the range of genes for pest control, but other genes are not yet widely available for use by farmers (Hilder and Boulter 1999; Sharma et al. 2002).

10.10 Managing Crop Complexity

The crops and pastures in farming systems can be managed to reduce the impact of pests. Rotating crops reduces the continuity of the food chain for pests, and thus prevents the build-up of damaging populations. In India, the rotation of sorghum with cotton, groundnut, sunflower or sugarcane[1] is used to reduce the damage by shoot fly, *A. soccata*, *S. sorghicola* and *C. angustatus* (Sharma 1985). In Western Australia, larvae of the scarab, *Heteronyx obesus,* cause damage when cereals follow pasture, but are not a problem when cereals follow lupins (Emery 2000). In India, damage from *A. soccata, C. partellus, H. armigera* and *S. sorghicola* is reduced when sorghum is intercropped with pigeonpea (Hegde and Lingappa 1996). Intercropping with red clover reduces the damage by the European corn borer, *Ostrinia nubilalis*, to maize in Canada (Lambert et al. 1987). Small areas of trap crops can be planted to attract pests, which can be destroyed using insecticides or biological control to protect the main crop. In southern Queensland and northern New South Wales in Australia, both summer and winter crops may be grown in the same year. Chickpeas grown in winter have been used to trap *H. armigera* before the pest moves onto the main summer crops (Miles et al. 2007).

The use of crop rotations and intercropping also has other benefits to the system such as provision of favourable habitats for the natural enemies of pests. Strip cropping, where two crops can be planted in alternating strips at widths used by harvesting equipment, can also be exploited to suppress pests by breaking up the spatial continuity of the crop and slowing movement of pests. Ma et al. (2007) found that strip cropping wheat and alfalfa in China improved the biological control of the wheat aphid (*Macrosiphon avenae*) by the mite, *Allothrombium ovatum*, by providing a better habitat for the mite. In Brazil, the egg parasitoid, *T. basalis,* is released into early-maturing trap crops, where it reduces the population of the stinkbug (*N. viridula*) by 54% (Correa-Ferreira and Moscardi 1996).

Crop growth can be improved by increasing sowing rates and by fertiliser use, which can reduce pest damage. A high sowing rate helps to maintain optimum plant

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[1] See Glossary for botanical names.

density and reduce insect damage in cereals (Gahukar and Jotwani 1980). Shoot fly and midge damage in sorghum are higher when plant densities are low because of a reduced ratio between the host plant density and natural populations of the target pests (Sharma 1985). Nitrogenous and phosphatic fertilisers decrease the impact on seed yield in sorghum by shoot fly, *A. soccata,* and the stem borer, *C. partellus* (Chand et al. 1979). Similarly the application of potash and nitrogen to sorghum reduces shoot fly and borer damage (Balasubramanian et al. 1986). However, for some pests and under some conditions, the addition of fertilisers may make the damage worse. Application of nitrogen to winter wheat increases the severity of attack by *Metopolophium dirhodum* and, under favourable conditions, by *Sitobium avenae*; under less favourable conditions, it can lead to lower populations of this species (Duffield et al. 1997).

Sowing time can be manipulated to reduce the exposure of the crop to pest populations. Synchronised sowing of sorghum early in the season reduces damage because the pests are not provided with a continuous food supply that allows multiplication on sequentially sown crops (Sharma 1993). Harvesting of a crop can reduce the resources available for the pest. For example, in pastures the quantity of resources available for pests is influenced by grazing intensity, and high stocking rates of sheep and cattle can reduce the food available for herbivorous insects and mites and thus the populations of foliage-feeding (East and Pottinger 1983; Grimm et al. 1994) and root-feeding pests (Roberts and Morton 1985). Farming systems can be managed to reduce the time that susceptible crops are exposed to pests, and to enhance the role of natural enemies, while retaining the productivity of the system. This is possible with rotations of crops, intercropping, trap crops where the pest is controlled, by increasing plant vigour through increasing sowing rates, or fertiliser use, by changing sowing times, and by grazing pastures with animals. The best options will vary between regions, crops and pests, and require an understanding of the plant-insect interactions.

10.11 Tillage

Ploughing a field before planting reduces the abundance and carryover of white grubs, grasshoppers, hairy caterpillars and stem borers in soil by exposing them to parasites, predators and adverse weather conditions (Gahukar and Jotwani 1980). It also kills weeds. Stubble management, such as collecting and burning stubbles and chaffy earheads reduces the carryover of *C. partellus* and *S. sorghicola* in sorghum (Sharma 1985). Stalks from the previous season should be fed to cattle or burnt before the onset of monsoon rains to reduce the carryover of stem borer (Gahukar and Jotwani 1980). Piling and burning of trash in the field at dusk attracts the adults of white grubs (*Holotrichia, Pachnoda, Melolontha*, etc.), blister beetles (*Mylabris*, *Cylindrothorax*, etc.) and the red hairy caterpillar (*Amsacta moorei*), and kills them. Reduced tillage is widely practiced in south-western Australia to conserve soil moisture, but can lead to greater survival of pests such as webworm (*Hednota* spp.), especially in grassy situations (Emery 2000). The widespread adoption of reduced tillage or no-till farming has been accompanied by an increase in pest problems, and an increase in the use of pesticides to control both pests and weeds.

10.12 Conclusions

Insect pests cause a substantial loss in the production and value of crops worldwide. There are many pest species which attack crops in rainfed farming systems, and the tools needed to manage them vary with each situation. Use of synthetic insecticides is increasing rapidly. They are easy to apply and the results are immediate, but the development of resistance in many pests requires a reduction in dependence on chemicals, and adoption of a more integrated approach using other tools such as plant resistance and cultural management; this involves the manipulation of farming systems to make them less favourable for the pest and more favourable for natural enemies. Different tools should be used in an Integrated Pest Management System, but vary for each crop/region/farm. A farmer growing grain legumes in a developing country may find that insecticides are unavailable or too expensive (Clement et al. 2000). Under these circumstances, use of cultivars with low to moderate levels of resistance can result in reduced populations of the pest, a substantial increase in the effectiveness of natural enemies, an increase in the benefits of cultural control methods, and consequently reduced crop loss. For a grower with better access to insecticides, pest-resistant varieties will reduce the number of pesticide sprays required, and thus, the cost of pest control. Our ability to improve pest management using new tools will be based on a better understanding of the underlying biological interactions between the plants and the insects for sustainable crop production.

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