Chapter 1

Chemical control in integrated pest management

Introduction

The human population continues to grow, especially in Asia and Africa, and the demand for food and other agricultural produce will continue to increase so it is not surprising that the market for pesticides continues to grow, despite innovative developments of genetically modified (GM) crops (Figure 1.1). In Europe, changes in legislation have significantly reduced the number of pesticides that can be marketed and their use must now form part of the EU Thematic Strategy on Pesticides (Stark, 2012). The restrictions have been in response to public perception of the risks associated with pesticide use in terms of residues in food and adverse effects on the environment. The perception is based erroneously on three false premises (van Emden and Peakall, 1996): that good crops were obtained in an ideal prepesticide era, that chemicals like pesticides never occur in nature, and that these unnatural pesticides are causing an increase in cancer. In practice, plants contain many chemicals which are highly toxic. For example, cyanide in cassava has to be removed by careful food preparation.

Without modern technology, including the use of pesticides, tripling world crop yields between 1960 and 1992, an additional 25–30 million square kilometres of additional land would have had to be cultivated with low-yield crops to feed the increased human population (Avery, 1997). Clearly, the use of pesticides plays an important role in optimising yields. Modern technology is changing and many pesticides, such as the persistent organochlorine insecticides, are no longer registered for use as newer, more active or selective chemicals take their place. Many chemicals are also being lost as companies are withdrawing support for them due to the cost of providing the additional data now required for registration, especially in Europe. At the same time, the agrochemical industry has invested in biotechnology and seed companies to exploit use of transgenic crops. The total area of transgenic crops has increased in 16 years to over 160 million hectares by 2011, involving over 16 million farmers in 29 countries (James, 2011) (Figure 1.2).

However, the growing of genetically modified crops has also aroused considerable public concern (Hill, 1998) and demands for legislation to control

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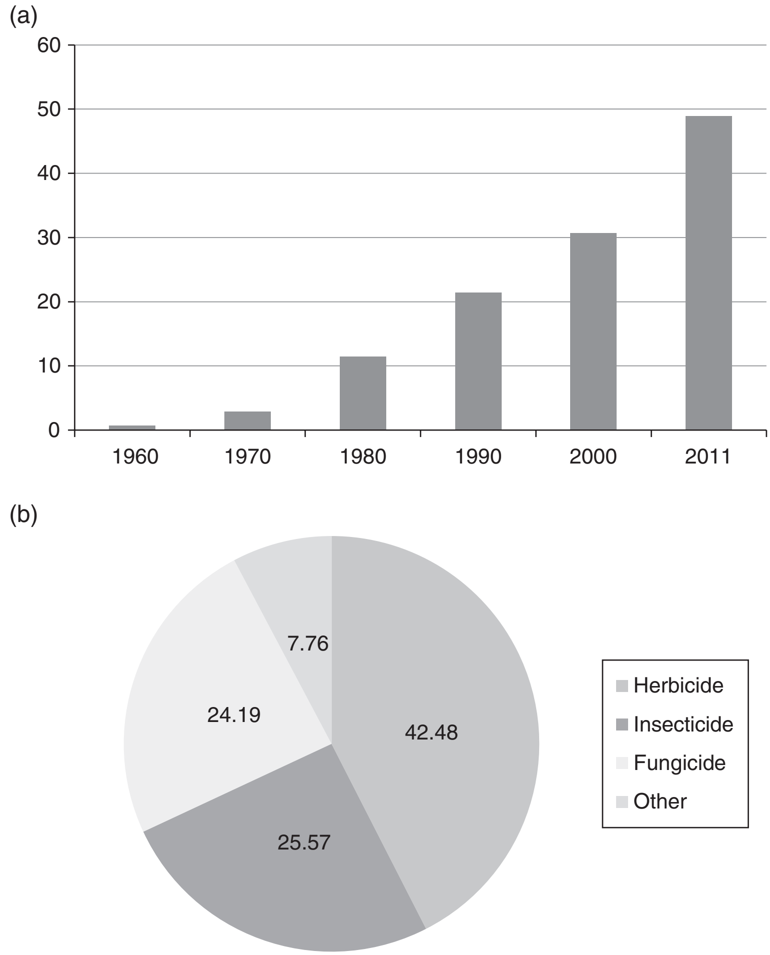

Figure 1.1 (a) Global increase in pesticide use in $billion. (b) Percentage of global pesticide market by type of pesticide.

their use. While in many cases the transgenic crop is marketed on the basis that less pesticide will be used, other transgenic crops are associated with the application of particular herbicides, notably glyphosate used with 'Roundup Ready' crops. For insect control, insecticidal proteins from the soil bacterium *Bacillus thuringiensis* (Bt) are used. These toxins are proteins, called Crystal (Cry) and Cytolitic (Cyt), which have to be ingested by the insect pests as they kill by binding to specific target sites in the insect's gut and disrupting the membrane. A single gene transfer expressing Cry 1 provides resistance to only one type of pest, and the gene has to express the toxin in the plant where the pest feeds and over the required period of crop growth when the pest causes economic damage. By stacking more than one Cry gene and combining with other insecticidal proteins, e.g.Vip toxins, insect control is improved and can extend the protection to a wider range of pests (Gatehouse, 2008), but other insect groups, especially sucking pests, may still have an

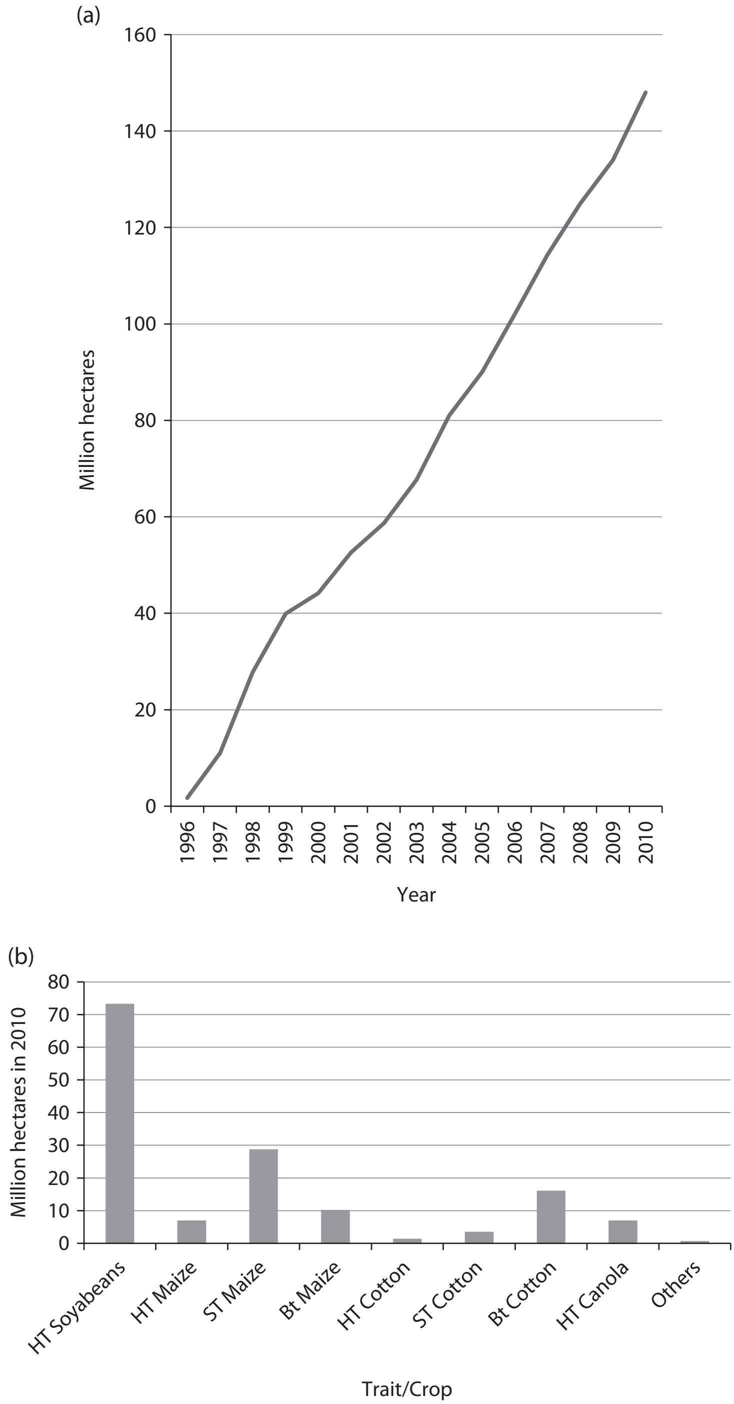

Figure 1.2 (a) Increase in global area of biotech crops. (b) Area of different biotech crops and traits in 2010. HT-Herbicide tolerant; ST-Stacked traits; Bt-GM crop with *Bacillus thuringiensis* toxin.

adverse effect on a crop and require an insecticide treatment (Hilder and Boulter, 1999).

One new approach involves enhanced resistance to lepidopteran pests, by developing a transgenic cotton expressing an Australian funnel-web spider venom toxin omega-hexatoxin-Hv1a and this has been claimed to be as effective as pyramided Bollgard II® cotton for controlling major cotton pests (Omar and Ali Chatha, 2012). However, research on several new ideas, such as using genetic engineering to improve natural plant defences to repel aphids away from a crop (Beale et al., 2006) or expression of dsRNA (Huvenne and Smagghe, 2010; Price and Gatehouse, 2008), may provide a new generation of insect-resistant crops.

Furthermore, it has been quickly appreciated that pests resistant to the toxin in transgenic plants can be selected, as occurs with overuse of a chemical pesticide, so the new varieties have been introduced with insecticide resistance management strategies (Merritt, 1998). The planting of genetically modified plants is therefore similar to use of new varieties from traditional plant breeding, and in relation to pest management their availability provides another tool to be integrated in the cropping programme.

Despite the criticisms of pesticide use, farmers will continue to need to apply them as chemical control remains the most cost-effective and rapid way of combatting the effects of weed competition and crop loss due to pathogens and insect pests. Our knowledge of the chemistry and suitability of a increasingly wide range of pesticides can now provide a more rational approach to their use and avoid the adverse outcomes associated with extensive use of the persistent organochlorines and the highly toxic organophosphate insecticides. International efforts have improved registration and pesticides now commercially available have been rigorously evaluated with greater harmonisation of test procedures. Unfortunately, in many countries, especially in less developed areas, farmers have inadequate training and too often use the least expensive pesticide, irrespective of its suitability for the pest situation. It is also frequently highly toxic but the farmers do not have the appropriate protective clothing. In consequence, farmers in some areas have applied too many pesticide treatments and suffered economically and with poor health.

Modern farming practices have more intensive production of relatively few crops over large areas, while more traditional farming in tropical countries has a sequence of crops that provide a continual supply of food for polyphagous pests. Both these farming systems provide environments for pest populations to increase to such an extent that crop losses will occur unless control measures are implemented. Although these losses can be extremely serious and can result in total loss of a crop in some fields, for example the effect of an invasion of locusts or armyworms, the extent of damage is usually far less due to the intervention of natural enemies.

Considerable efforts have been put into training by means of farmer field schools, especially in relation to lowland irrigated rice production in South East Asia in an attempt to get farmers to recognise the importance of natural enemies. The difficulty for the farmer is knowing when a pest population has reached a level at which economic damage will occur so that preventive action can be taken. This decision should take into account the presence of

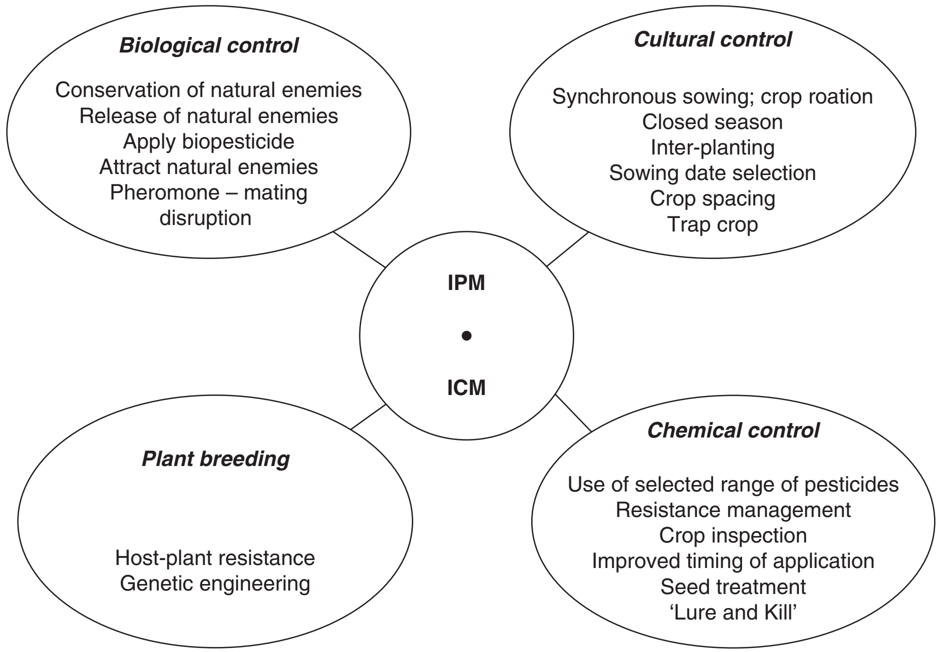

Figure 1.3 IPM/ICM – the need to integrate different techniques.

natural enemies but sampling for these can be quite time consuming. Conservation of natural enemies is crucial in minimising the need for any chemical control, especially in the early vegetative stages of crop development. Areas with alfalfa or other fodder crops may provide a refuge for natural enemies; thus in Egypt, berseem clover assists the overwintering survival of lacewings which are important predators of cotton pests. However, the farmer will need a pesticide when quick action must be taken to avoid economic crop loss. Various methods of assessing pest populations are used to assist farmers determine when a pesticide may be applied as part of an integrated pest management programme.

Integrated pest management (IPM) utilises different control tactics (Figure 1.3) in a harmonious manner to avoid as far as possible undeirable side-effects on the environment. To many, this means avoiding the use of any chemical pesticide and growing crops organically but in many cases, such a system is not sustainable where high yields are required. In some situations, the public will pay a premium for organic produce but yields and quality can be lower in comparison with crops receiving minimal intervention with chemical control. In some cases, organic produce is said to taste better and this may be due to the choice of crop variety rather than not using any pesticide.

Weeds are frequently the most important factor during crop establishment at a time when demands for farm labour are high. Traditional hand weeding is very labour intensive and often not very effective, while general disturbance of soil by cultivation can increase erosion of some soils. Virtually weed-free conditions are possible with the range of herbicides now available and on some well-structured soils it is no longer necessary to plough every year as seed can be direct drilled after applying a broad-action herbicide, that is inactivated on contact with the soil. The area with a 'no-till' approach has increased as retaining crop residues conserves the soil and many of the beneficial organisms, such as earthworms, that are important in maintaining soil fertility. Their activity also has increased conservation of ground water so that crops suffer less during periods of drought. In Africa, no-till can be combined with growing strips of crops, interspersed with a line of *Faidherbia albida* trees, the 'fertiliser tree', as it sheds its nitrogen-rich leaves and contributes to improving the fertility of the soil (Barnes and Fagg, 2003).

Herbicide use has increased most where labour costs are high, there is a peak labour demand or where mechanical hoeing will cause damage to the young crop. In conjunction with other agronomic practices such as tie ridging and planting along contours, herbicide use can reduce soil erosion by minimising soil disturbance.

Improved row weeding either by hand hoeing or by application of a herbicide increased yields by up to 35% in West Africa (Carson, 1987). With changes to direct seeding of rice and other factors, herbicide usage has increased in many crops in the tropics where traditional labour is no longer readily available for hand weeding or hoeing. In order to minimise use of herbicides, methods of selective application have been developed and used in precision farming.

Wherever possible, farmers will select disease-resistant cultivars to reduce the need for fungicide treatments but in some situations, the farmer will continue to grow varieties which are susceptible to particular pathogens because of other qualities, such as taste and yield. The extensive damage to potato crops due to *Phytophthora infestans* that led to the Irish famine can be avoided by careful use of fungicides. Until a GM potato has been developed with resistance to *Phytophthora*, the risk of selecting strains resistant to the fungicide can be reduced if the number of applications is restricted by monitoring climatic conditions so that treatments can be timed to coincide with periods favourable to the pathogen. Field application of fungicide will often improve the quality at harvest and allow longer storage.

The visibility of an insect is in no way related to the amount of damage and economic loss that can occur. Often farmers react to the presence of a low population of insects and may fail to distinguish between pest and beneficial species. The intervention of predators and parasitoids will often suppress a pest population such that economic damage is avoided. Thus precipitate action with insecticides, especially those with a broad spectrum of activity, often disrupts this biological control too early in the crop and in the absence of natural enemies, pest populations can increase dramatically. Furthermore, plants have evolved to withstand considerable damage due to insects by compensatory growth and production of chemicals toxic to the pests. Thus in integrated pest management programmes (Matthews, 1984; van Emden and Peakall, 1996), pesticide use should always be confined to when a pest population has exceeded an economic threshold. The difficulty for the farmer is knowing when that economic threshold has been reached and then being able to take rapid action with minimal disruption of beneficial insects.

Pesticides

The viewpoint expressed more than 40 years ago by Smith (1970), that pesticides remain our most powerful tool in pest management, is still true today, even with the enormous rapid growth in commercial use of GM crops. Pesticides remain crucial when rapid action is needed to prevent major crop losses. Southwood (1977) stressed the need to conserve pesticides as a valuable resource and reduce the amount of chemical applied and the number of applications to decrease the selection pressure for resistance, prolong the useful life of each pesticide and reduce environmental contamination. Pesticides will therefore continue to be an important part of IPM programmes. There is, however, a greater realisation that pest management is only part of the wider requirement of integrated crop management (ICM) as investment in controlling pests can only be economic if there are sufficiently high potential yields. In practice, those marketing the produce, the supermarket and food processing companies, are having a greater influence on pesticide use by insisting on specific management programmes.

Integrated crop management

Prior to the widespread availability of chemical pesticides, farmers had to rely first and foremost on the selection of cultivars resistant to pests and diseases. Unfortunately, not all resistant cultivars were acceptable in terms of the harvested produce due to bitter taste, poor yield or some other negative factor. Farmers therefore adopted various cultural techniques, including crop rotation, closed seasons with destruction of crop residues, intercropping and other practices to mitigate pest damage. Biological control was also an important factor in suppressing pest populations, but many of these basic techniques were forgotten due to the perceived convenience of applying chemical controls.

Although the use of modern methods of manipulating genes in transgenic crops merely speeds up the process of selection of new crop cultivars, many who question the development of these GM crops have a strong influence on governments who fail to see the scientific importance of the new technology. Part of the problem is that farms in some countries have grown only one of two GM crops over vast areas and neglected the need for crop rotation and closed seasons to break the cycle of pests. Whether GM crops will provide a sustainable system of crop production has yet to be demonstrated. As indicated earlier, the introduction of the Bt toxin gene into plants will increase mortality of certain lepidopterous pests but it will not affect many other important insect pests and its effect on lepidoptera could be short-lived if insects resistant to Bt are selected.

Even partial plant resistance to a pest is important. As van Emden (1972) pointed out, only half the dosage of the selective insecticide pirimicarb was required on plants with slight resistance to the cabbage aphid *Brevicoryne brassicae*. With the lower dosage of insecticide, the natural enemies were unaffected and controlled any of the pests that survived. In some crops, particularly those in glasshouses, the use of a low dosage of a non-persistent insecticide can be followed by release of natural enemies (GreatRex, 1998).

A classic example is the application of resmethrin or the biopesticide containing the fungal pathogen *Verticillium lecani* to reduce whitefly *Trialeurodes vaporariorum* populations prior to the release of the parasitoid *Encarsia formosa*. This is important where light intensity and temperature are unfavourable to *Encarsia* early in the season (Hussey and Scopes, 1985; Parr et al., 1976).

Area-wide integrated pest management

Individual farmers can adopt an integrated pest management programme, but increasingly, many of the control tactics need to be implemented on a much larger scale. A farmer can choose a resistant cultivar, monitor the pest population and apply pesticides if pest numbers reach economic significance, and subsequently destroy crop residues harbouring pests in the off-season. A good example has been in Central Africa, where cotton farmers grow a pubescent jassid-resistant variety (Parnell et al., 1949), time insecticide applications according to crop monitoring data (Anon, 1998; Matthews and Tunstall, 1968; Tunstall and Matthews, 1961), then uproot and destroy their cotton plants after harvest and bury crop residues by ploughing. Detailed recommendations were provided to farmers via a crop manual updated frequently to reflect the availability of different varieties and changes in insecticides. However, many tactics are only effective if all farmers within a defined area adopt them. A feature of the Central African programme has been a nationally accepted restricted list of recommended insecticides, discussed in the section entitled Resistance to pesticides.

The selection of control techniques and their subsequent regulation throughout a given area or ecosystem, irrespective of county or national boundaries, is regarded as pest management. A distinction is made between the use of integrated control by individuals and pest management implemented co-operatively by everyone within the area. Pest management may emphasise one particular control technique but in general, there will be reliance on its harmonisation with other tactics. Furthermore, it must be a dynamic system requiring continual adjustment as information on the pest complex and control tactics increases. Modern information technology with computer databases, the internet and 'expert' systems can provide up-to-date information to farmers and their advisers.

Resistance to pesticides

The agrochemical industry has become more concerned about the impact of pesticide resistance and has recognised the role of IPM in reducing selection of resistant populations (Urech et al., 1997). Efforts have been made to devise resistance management strategies, to avoid disasters such as the cessation of cotton growing in parts of Mexico and Australia, due to DDT resistance.

Selection for resistance occurs if a particular chemical or chemical group is applied too frequently over a period to a given pest population. Initially, the impact of resistance was noted in glasshouses with a localised population but resistance of red spider mite to organophosphates was also apparent on outdoor irrigated vegetable crops in the tropics where the same acaricide had been used throughout the year on different crops. Thus resistance develops rapidly if most of a pest population is exposed to a specific pesticide, if the pest can multiply quickly or if there is limited immigration of unexposed individuals. The user is tempted to increase either the dosage or the frequency of application, or both if control measures are unsatisfctory, but this increases the selection for resistance.

Resistance selection is reduced if part of the pest population is on alternative host plants or other crops which are not treated with the same chemical Thus, in introducing transgenic crops with the Bt toxin gene, a proportion of non-Bt crop is required as a refuge. Resistance to insecticides by the cotton bollworm *Helicoverpa armigera* has not been a serious problem in Africa, where large areas of maize and other host plants are untreated. However, in West Africa resistance to deltamethrin has now been reported and this may be because farmers are using pyrethroids increasingly on vegetable crops in the same locality. Major problems of resistance in *H. armigera* have occurred in India and China where farmers have applied pyrethroids extensively with knapsack sprayers. Spray directed downwards from above the crop canopy was poorly deposited where the bollworms were feeding on buds, and in consquence lack of control led farmers to repeat treatments at frequent intervals. The continued exposure of larger larvae to pyrethroid deposits without significant mortality quickly led to resistant populations. The situation was made worse by the availability of a range of products with different trade names but often based on the same or similar active ingredient; thus when the farmer thought he had changed to a different pesticide, in reality it was the same. The adoption of Bt cotton while reducing the number of sprays against bollworms did not always reduce spray applications as jassids and other pests were unaffected by the Bt toxin.

In Australia, the onset of pyrethroid resistance led to the introduction of a pragmatic resistance management strategy, which limited the application of any pyrethroid insecticide to a brief period each year irrespective of the crop. With the introduction of Bt cotton, attention has now focused on assessing resistance to the Cry1Ac, Cry2Ab and Vip3a toxins (Downes and Mahon, 2012; Downes et al., 2007). However, with refuge areas of conventional cotton a more refined resistance management programme is still advised and generally there should be no more than two sequential sprays of any chemical group (Figure 1.4) (Anon, 2009). With Bt cotton, the concern is the need for effective control of sucking pests. Generally, the amount of pesticides used on GM and conventional cotton has decreased (Figure 1.4b) with more farmers implementing integrated pest management.

Apart from the temporal control for pyrethroid insecticides, an acaricide resistance management programme has been tested, whereby acaricides with different modes of action were used for only two seasons in one of three zones (Anon, 1998), the acaricides being rotated around the zones over a 6-year period in Zimbabwe (Figure 1.5). In each of these resistance management programmes, the aim was to avoid a pest population being exposed for too long to a particular pesticide. Whatever strategy is adopted, careful monitoring of resistance levels in different localities is required so that appropriate changes can be made to the strategy when needed.

(a)

Insect Pest	STAGE 1	STAGE 2	STAGE 3	STAGE 4	
Helicoverpa	Foliar Bti Baculovirus →	→	→	→	Excludes Bollgard II refuges
Aphids	Pirimicarb → At planting aldicarb or phorate Paraffinic oil	→			Max. 2–non consecutive applications Do not follow with pirimicarb. No restrictions
Mites	Etoxazole →	→	→	→	Max 1 application
Helicoverpa		Rynaxpyr →	→	→	Max 3 applications
Mites	Dicofol →	→	→	→	Max 2 applications
Aphids and Mites			← Diafenthiuron →	→	Max. 2 non consecutive
Aphids	Pymetrozine →	→	→		
Helicoverpa		←	Indoxacarb →	→	Max 3 applications
Aphids	Spirotetramat →	→	→	→	Max 2 applications–non consecutive
Mites and *H. punctigera*	Abamectin →	→	→	→	Max 2 applications*
Helicoverpa	Emamectin →	→	→	→	Max 2 applications*

*Max 3 applications of Abamectin /Emamectin not 4. Less selective insecticides may be used only in Stages 3&4.

(b)

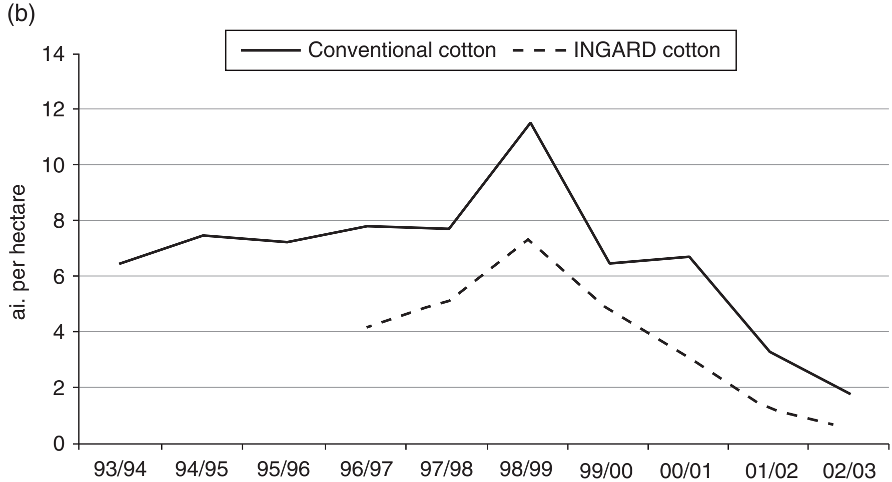

Figure 1.4 (a) Insecticide resistance management programme in Australia. Abbreviated version 2011–2012; recommendations from www.cottoncrc.org.au/industry/Publications/Pests_and_Beneficials. (b) Decline in pesticide usage per hectare in Australian GM (Ingard) and conventional cotton.

Fungicide resistance

Similarly with fungicides, if a chemical with a particular mode of action is used repeatedly, resistant strains of the fungi will be selected. Reduced dosages of fungicides showed significant selection for resistance to demethylation inhibitor (DMI) fungicides (Metcalfe et al., 1998), but the strength of selection varied with fungicide, position of infection in the crop canopy and position on individual leaves. Clearly, with variations in deposits within a canopy and degradation of

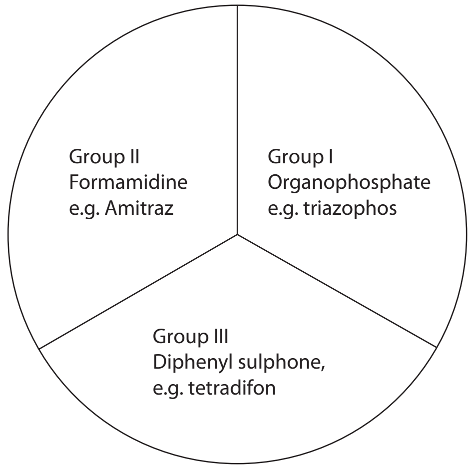

Figure 1.5 Idealised acaricide rotation scheme based on a system that was used in Zimbabwe.

deposits, fungi will be exposed to low dosages of fungicide. Thus selection needs to be minimised by better disease forecasting so that fewer applications are required and those needed can be timed more accurately. Making sure the optimum dosage reaches where the infection is within the canopy is clearly most important and led to changes in nozzle selection to improve deposition of fungicides more strategically on plants.

New fungicides have been developed, including second-generation succinate dehydrogenase inhibitors (SDHI), but they need to be used in mixtures or in sequence with other fungicides to minimise selection for resistance. In discussing the future of resistance management, Hollomon (2011) is looking for more research on cell biology and modelling protein structures and target sites to find new modes of action that can be delivered not only through new fungicide sprays or seed treatments, but also by new transgenic crops.

Herbicide resistance

Changes in the weed species often follow frequent use of a herbicide in one particular area, as the species tolerant to the chemical can grow without competition. This has resulted in the need for different and often more expensive herbicides or combination of herbicides. Resistance to a particular herbicide has become evident more slowly compared to insecticides or fungicides, as the generations of weeds overlap due to dormant seeds and there are fewer generations each year. Resistance to the trazines, acetolactate synthase or actyl CoA carboxylase inhibitors due to mutated target sites (Schmidt, 1997) has been followed by serious weed problems with glyphosate resistance where ‘Roundup Ready’ GM crops have been grown. One response to the glyphosate resistance is to stack resistance to a 2,4-D herbicide. These GM crops will then be sprayed with a mixture of glyphosate and a 2,4-D choline, the latter being less volatile than traditional formulations of 2,4-D amine or ester (Green, 2012).

Some grass weeds have multiple resistance to herbicides with different modes of action, As an example, resistance of blackgrass (*Alopecurus* *myosuroides*) was first detected in 1982 and affected over 700 farms in the UK (Moss et al., 1999), due to many years of continuous winter wheat production (Orson and Harris, 1997). Chauvel et al. (2001) studied cropping systems to decrease blackgrass densities and showed that herbicides were most effective when combined with non-chemical practices. In discussing the role of mixtures and sequences of herbicides to delay the onset and limit the spread of multiple herbicide-resistant populations in winter cereal crops, Bailly et al. (2012) included the use of residual herbicides. Beckie and Tardif (2012) also discussed strategies and showed the potential for stacked herbicide resistance traits to manage weed biotypes. Further information on herbicide resistance in relation to herbicide-tolerant crops is given by Vencill et al. (2012) and suggestions for reducing the risks of herbicide resistance are discussed by Norsworthy et al. (2012).

Timing of spray application

One of the major problems of using pesticides is knowing in advance what pesticide and how much of it will be required during a season. To facilitate forward planning, some farmers may prefer a prophylactic or fixed calendar schedule approach but to minimise pesticide usage, it is preferable to restrict treatments and only apply them when crop monitoring indicates a definite need. Forecasting pest incidence is an important means of improving the efficiency of timing applications but is not always very accurate due to variations in weather conditions and survival of pests from the previous season. However, sugar beet growers in the UK benefited from a virus yellows warning scheme (Dewar, 1994). Modelling of the incidence of virus yellows had shown that up to five severe epidemics could have occurred since the major epidemic in 1974 (Figure 1.6) if improved pest management practices had not been

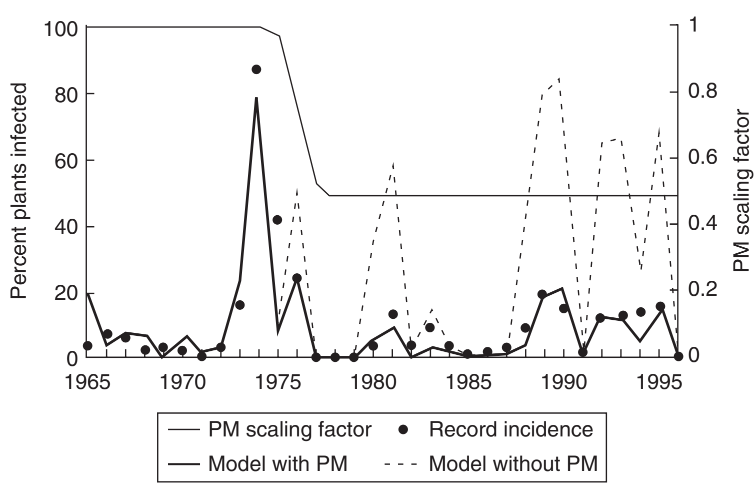

Figure 1.6 Incidence of infected sugar beet and predicted levels as shown by a model to indicate impact of integrated pest management.

adopted (Werker et al., 1998). Short-term prediction of the potential for a disease outbreak based on weather forecasts can be useful for some diseases, where the temperature has to exceed a certain minimum coincident with high humidity and/or leaf wetness. Mini meteorological stations can be set up to measure the conditions in crops sensitive to certain pathogens.

Generally sprays, should be applied immediately after preparation but if weather prevents completion of a spray operation, Stewart et al. (2009) have reported that some postemergent herbicides can be applied up to 7 days later without affecting their efficacy.

Economic thresholds

Ideally, conservation of natural enemies would reduce the need for farmers to use any insecticides but where climatic conditions and cropping practices result in an increase in pest populations, quick action is needed to prevent economic losses. The actual loss of a crop will depend on when the pest infestation occurs during crop development and its severity. Often, a crop can sustain some pest damage if there is sufficient time for plants to respond and compensate for the damage. The problem for farmers is deciding when to take action.

One aspect of IPM is to use an economic threshold, defined as the population density at which control measures should be applied to prevent an increasing pest population from reaching the economic injury level. This economic injury level is the lowest population density that will cause economic damage (Onstad, 1987; Pedigo et al., 1986; Stern, 1966). Changes in the market prices of crops make it very difficult to be precise about economic thresholds, so based on past experience, farmers may have to follow a more pragmatic 'action threshold'. In some countries, farmers can employ independent crop consultants who will inspect fields and advise when chemical control is needed. However, in most situations it is the farmer who has to decide, so simple techniques of monitoring pest populations and/or damage are needed, if the number of chemical treatments is to be minimised.

Timing of spray applications on cotton in relation to pest populations was possible by using sequential sampling methods to reduce the time needed to examine plants in the field (Figure 1.7). The system allowed a decision to spray if the population exceeded a set threshold, even if the whole field had not been sampled, but generally required sampling to continue if low populations were present. To simplify the crop monitoring, pegboards were developed (Beeden, 1972; Matthews, 1996), the design of which has been adapted in different countries according to which pests are dominant and whether sampling considers the presence or absence of natural enemies (Figure 1.8). While it is important to avoid a spray treatment if large numbers of predators, such as lacewings, are present, natural enemies are generally less easy to detect.

With the introduction of Bt cotton, scouting is less important for bollworm eggs or larvae but is still required for sucking pests. Whether to spray or wait can be a dilemma and emphasises the importance of research in a particular area to assess the extent of biological control at different stages of crop

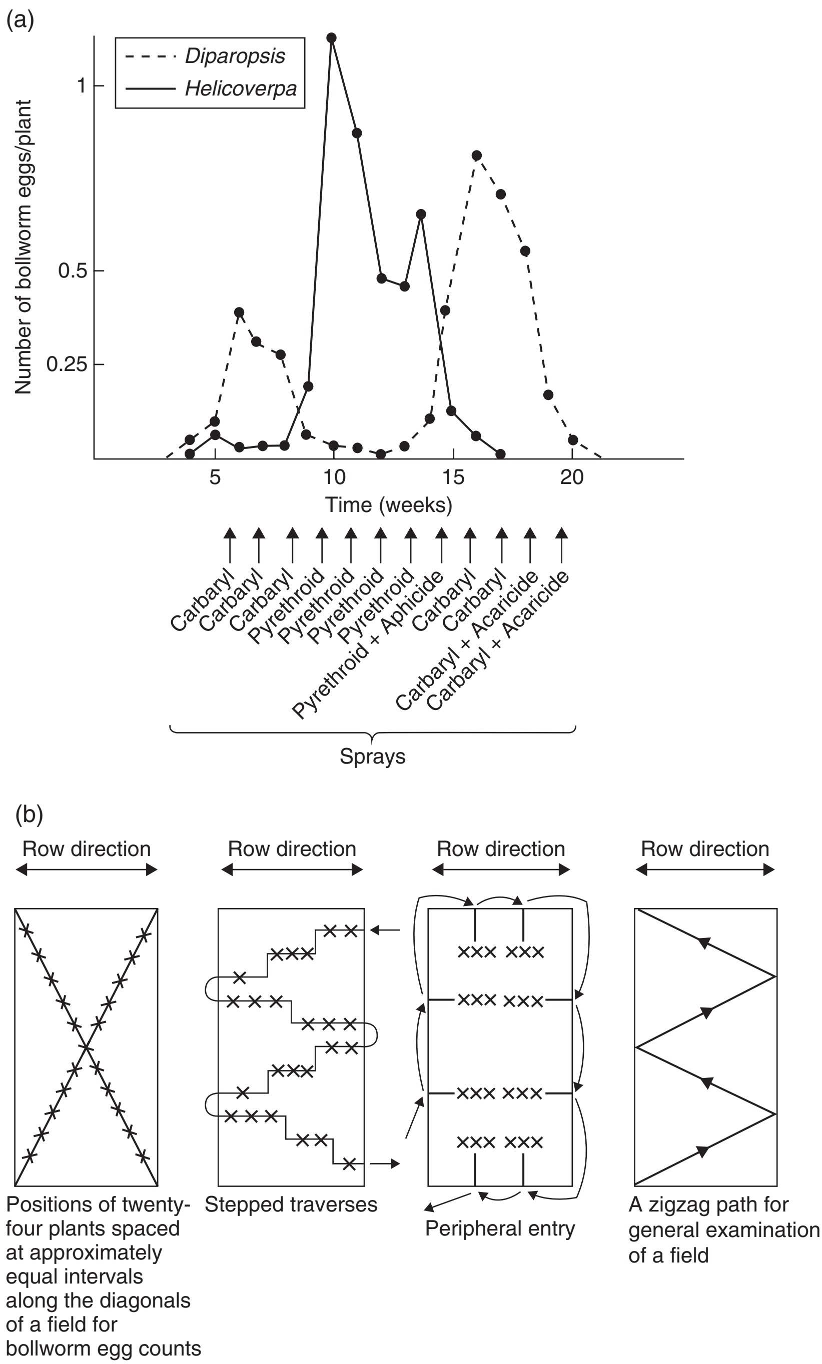

Figure 1.7 Sampling schemes to monitor pests in different areas of a cotton field.

Figure 1.8 Pegboard for small-scale cotton farmer to record insect pests. For a colour version of this figure, please see Plate 1.1.

development. Generally, if the 'action threshold' has been set correctly, insecticide is applied only when a pest infestation is no longer checked by natural controls and intervention is essential to avoid crop loss.

Other sampling systems have been devised depending on the crop and pest. Pheromone traps provide a selective and effective way of sampling low pest densities to determine whether an infestation is likely. At higher pest populations, the trap data are less reliable, as their use only indicates when pests are active and crops need to be monitored. Similar sticky traps or traps with a food attractant may be more appropriate for certain pests. Some scientists have suggested timing of treatments based on crop damage assessments but it is likely that it is too late to justify insecticide treatment when damage is observable. As an example, control of an insect vector of a viral disease requires action at very low pest populations, before the symptoms of disease can be seen, although reduction of further spread of an infection may be checked by a late treatment.

Application sites and placement

A key issue is the risk of 'spray-drift' beyond the field boundary, especially if there is another crop susceptible to a herbicide, there is surface water or a ditch which could be contaminated by the pesticide (Croxford, 1998), or there are bees downwind of insecticide-treated fields. Protection of hedgerows around fields is also of crucial importance to avoid contaminating the habitat of important populations of natural enemies. Field boundaries are also important habitats for game birds and conservation of other wildlife (Boatman, 1998; Forster and Rothert, 1998; Oliver-Bellasis and Southerton, 1986) (Figure 1.9).

To minimise the risk of drift, some countries now have a legal requirement for a 'no-spray' or 'buffer' zone around fields or at least along the downwind edge of a field and to protect surface water (van de Zande et al., 2000) (Figure 1.10). The width of the untreated buffer zone (UBZ) really depends on

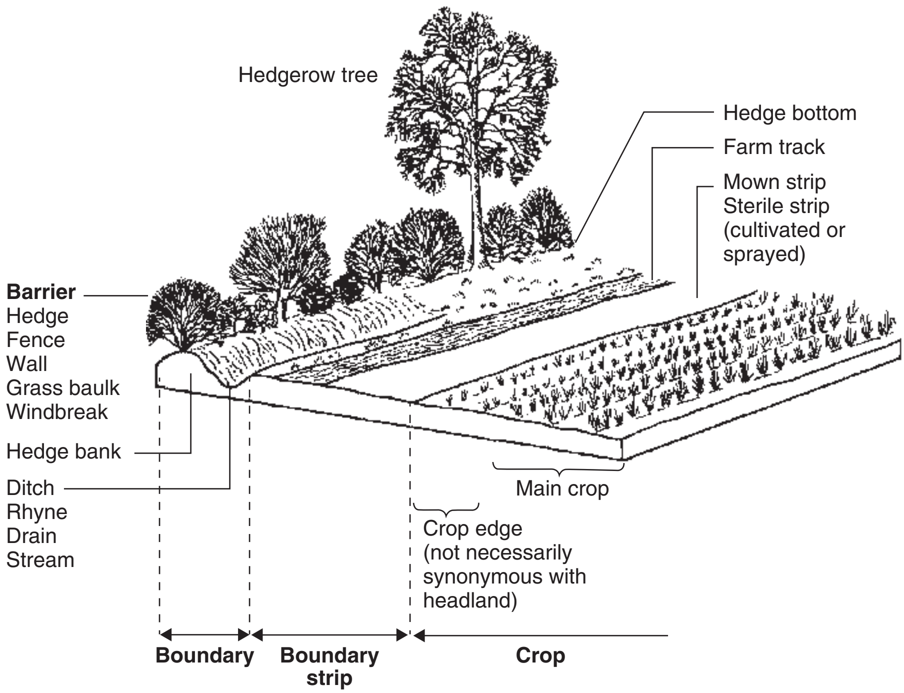

Figure 1.9 Principal components of arable field margin (from Greaves and Marshall, 1987).

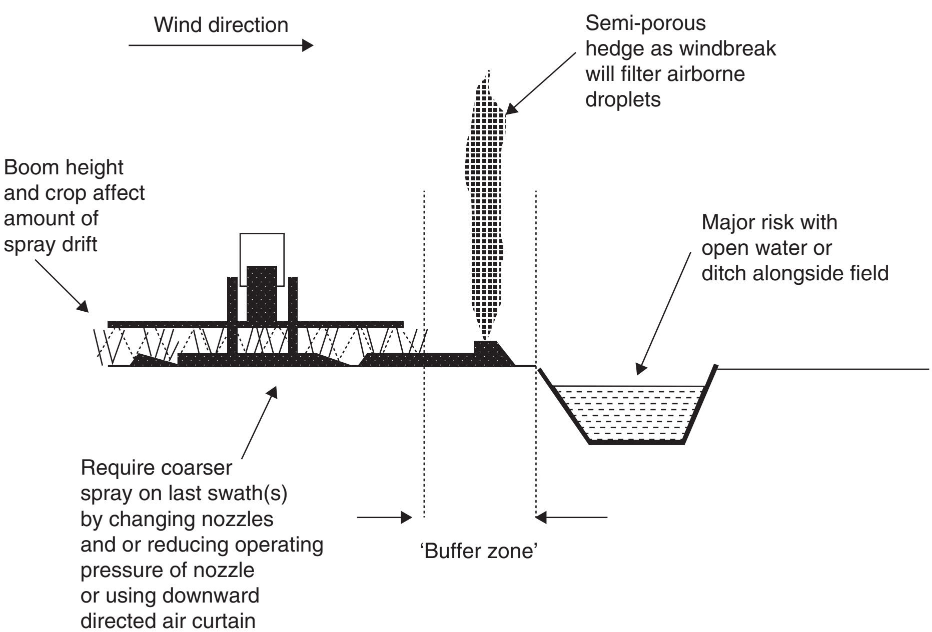

Figure 1.10 Untreated buffer zone.

the spray droplet spectra, the height of release of the spray and wind conditions. To simplify the procedure, some countries have fixed distances downwind from the field boundary; thus, in the UK the UBZ was set at 5 metres between the side of a ditch or watercourse and the edge of an arable crop and 18 metres in orchards. However, following concern about the amount of crop area affected in the UK (Orson, 1998), a Local Environmental Risk Assessment for Pesticides (LERAP) was introduced where the UBZ can be reduced for ground-based arable spray equipment from 5 metres to effectively 1 metre from the top of the bank of a ditch if the spray method and equipment meet LERAP approval (Gilbert, 2000) (see also Chapters 4, 5 and 12). However, concern about drift of certain pesticides has led to adoption of wider buffer zones; thus, when spraying chlorpyrifos in the UK, farmers have used a 20 metre-wide buffer zone adjacent to watercourses in addition to applying it with low-drift nozzles.

Longley et al. (1997) and Longley and Sotherton (1997) examined the extent of drift into field boundaries and hedgerows and Raupach et al. (2001) examined the porosity of windbreaks in relation to the interception of spray. According to Lazzaro et al. (2008) where there is a hedgerow with an optical porosity of 74–75%, the aerial drift caused by common broadcast air-assisted sprayers becomes negligible at a distance of 6–7 m. Miller et al. (2000) showed that differences in plant structure will affect the extent of drift at field margins (see Figure 12.7). An established vegetative strip will significantly decrease drift compared with a cut stubble due to the filtration of the droplets (Miller, 1999). A grassed buffer strip, especially if sown perpendicular to the slope, will also restrict run-off of pesticide (Patty et al., 1997). Heijne (2000) reported the use of artificial netting as an alternative to a hedge, which will take time to get established. The height and porosity of the netting determine the extent to which drift is reduced.

Crop monitoring for a pest may indicate a particular focus of infestation in a crop and permit localised treatment to reduce the spread of the pest and avoid the cost of a treatment to the whole area. Some infestations may be initially at the edges of fields; for example, pink bollworm may spread from villages if stalks have been stored for fuel. Many wind-borne insects collect on the lee side of hedges (Lewis, 1965) or other topographical features. An isolated tree in a field can affect the initial distribution of red spider mites due to its effect on air movement across a field. If detected early, the initial patches of infestation can be treated with a knapsack sprayer to avoid treating the whole field.

Spatial differences within a field or crop canopy can also be exploited by using localised treatments to allow greater survival of natural enemies. Discrete droplets leaving areas untreated are generally more favourable than high-volume treatments where all surfaces get wetted, when natural enemies inevitably are exposed to pesticides. Theoretically, some treatments can be localised by using an electrostatically charged spray, particularly to avoid pesticide fall-out on the soil and adversely affecting soil-inhabiting predators. However, this approach has not been exploited. Soil application of a systemic insecticide as granules or seed treatment will generally control sucking pests with less risk of direct effects on their natural enemies.

Conservation of natural enemies is especially important in perennial crops so pesticide treatments may need to be separated in time. Thus, treatment of strips through an orchard with a non-persistent insecticide provides control of the pest and natural enemies can re-establish from the untreated sections of the orchard which are treated several days later.

The importance of restricting pesticides as far as possible to the actual target is fundamental to good pest management and is considered in more detail in subsequent chapters.

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