1 Why Use Natural Enemies?

Humans share the planet Earth with about 8.7 million species of complex organisms, those whose cells have nuclei. If we add the number of species of microbes without nuclei, this number would be far greater. Each species eats, grows, and reproduces in different ways in different locations around the world, but virtually no species does this in isolation. All species are interconnected to some extent, with some organisms more dependent on others, especially those higher in the food chain. Tigers would not live long without their prey being available, just as rabbits would not survive for long without plants to eat. Humans have quite a dominant position in many ecosystems and we depend on many other species for food and shelter. Especially because the influence of humans is so pervasive throughout the world, humans also compete with many organisms. When other organisms compete for resources with humans or negatively affect humans in other ways, they are generally regarded as "pests."

Humans have been plagued by pests since before recorded history. A pest can be formally defined as any organism that competes with humans for resources used for food, fiber, or shelter. These pests eat crop plants used for food or trees used for lumber as well as plants, such as cotton, used for fiber. Pests can also disrupt human and animal health and well-being, making organisms directly affecting human and animal health, such as mosquitoes carrying pathogens that cause diseases like malaria or dengue, pests too. Thus, the definition of the term pest needs to be broad because of the great diversity in the ways that pests negatively impact humans. Pests are as diverse taxonomically as they are in the ways that they compete with humans, ranging from microorganisms to plants and to animals with or without backbones. With such variability comes a variety of adaptations making some organisms that compete with humans tough adversaries.

There are many different means for controlling pests (see Chapter 19) but this book is principally covering control methods using living organisms, a strategy called biological control. We will therefore not be covering all pests but only those specifically targeted by biological control. The major types of pests that are addressed by biological control include invertebrates (especially arthropods that often attack plants or animals) and vertebrates, weedy plants, and microorganisms, called plant pathogens, that attack plants (often crop plants or forest trees).

1.1 Historical Perspective on Chemical Pest Control

Humans have always needed to control pests affecting them directly, such as mosquitoes or bed bugs, or competing with them for a great diversity of resources. Through the ages, pest-control practices have changed dramatically. The earliest known record for the use of naturally occurring compounds for pest control was around 2000 BCE (BC) in a Hindu book written in India that referred to using poisonous plants to control pests. At the time of the pharaohs, the ancient Egyptians used compounds extracted from plants to help with insect control. Around 1000 BCE, Homer the Greek mentioned using sulfur as a fumigant to control pests, and in 77 BCE, Pliny the Roman reported that arsenic was insecticidal. Around 1100 CE (AD) soap was used as an insecticide in China. From the 1500s to 1600s, approaches to pest control seem to have changed. Plants having insecticidal compounds were used more extensively by Europeans, so that in the 1800s tobacco extracts and nicotine smoke were applied for insect control. Around the same period, the use of inorganic compounds also increased for pest control. In the 1800s, we see the first mention of a mixture concocted for pest control that became widely used: Paris green, an arsenic-based compound, was developed and applied against Colorado potato beetles, *Leptinotarsa decemlineata*, in the United States. Bordeaux mix, a combination of copper sulfate and hydrated lime, was developed in 1882 in Bordeaux, France, to control plant-pathogenic fungi on grapes and other fruit.

However, throughout these times, the overriding methods for pest control were cultural practices, such as destroying pest-infested fields, allowing them to lie fallow, and rotating crops. For example, when soybean crops are rotated with corn (maize), the populations of soil-dwelling nematodes that attack soybean roots decline when corn is growing, and after the corn crop has been harvested, soybeans can again be planted in that field. Other cultural controls included practices such as altering dates for planting and harvesting, using trap crops, planting mixtures of crops, managing drainage, and removing crop residues that harbor pests. Through use of cultural controls, growers were basically manipulating and augmenting the naturally occurring processes of pest suppression.

Several developments took place between World Wars I and II, setting the stage for major changes in pest control. Industries developed methods for large-scale production and chemists vastly improved their abilities to synthesize chemicals. In 1939, both DDT for control of insects and 2,4-D for control of weeds came on the scene. These extremely effective compounds revolutionized pest control. Since that time, a cascade of different compounds belonging to an increasing number of chemical classes have been synthesized for pest control. Most of the early compounds were effective against a broad spectrum of pests, killed pests very quickly, and were relatively easy to apply using spray equipment. Availability of these synthetic chemical pesticides vastly improved the potential for successful harvests and, consequently, use of these compounds skyrocketed.

Use of pesticides (such as insecticides, fungicides, herbicides, etc.) over time increased, but these changes are not easy to quantify. Figure 1.1 illustrates the increase in sales of different types of pesticides on the worldwide market between 1980 and 2011.

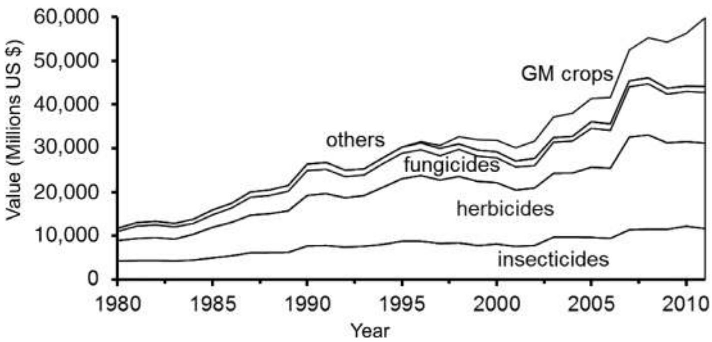

Figure 1.1 Worldwide pesticide markets from 1980 to 2011. GM crops = genetically modified crops. Data compiled from the annual reviews of the British Agrochemicals Association (updated by Roy P. Bateman from Bateman, 2000).

In 2011, while 55 percent of pesticide sales occurred in North America and Europe, a significant amount (45 percent) of pesticides were sold in Asia, South America, and the rest of the world. The total value of pesticide sales increased more than 3.5 times between 1980 and 2011. Looking at the value of pesticides can be a misleading statistic, because, over time, the potency of pesticides has increased, confounding comparisons through time (e.g., moving back through time, more of a compound had to be purchased for a similar effect). An alternate way to look at this could be to evaluate the area of land on which pesticides were applied, but unfortunately such data are not readily available. A major fact to be gleaned from Figure 1.1 is that among the numerous types of pesticides, from 1980 to 2011 the use of herbicides increased substantially, although the use of fungicides and insecticides also increased. Also during this period, genetically modified (GM) crops for insect and weed control entered the market (in 1996) and have become widely adopted in industrialized and developing countries. By 2011, GM corn, cotton, soybeans, and canola, the only large-acreage GM crops available at the time, accounted for 22.4 percent of the total sales ('GM crops' in this context include those containing insecticidal toxins and/or resistant to herbicides). Other crops designed to control insects, weeds, and viruses are entering the market and are predicted to become an increasingly larger component of the value of the global pesticide market.

The bottom line is that the global market for pesticides is projected to reach 3.2 million tons in 2019, valued at US $81.18 billion worldwide. In 2007 alone, greater than 2.4 billion kilograms of pesticides were applied worldwide and the United States, with a large area of agricultural land, accounted for 20 percent of this use. However, in the United States in 2013, it was estimated that 80 percent of pesticide use was agricultural while 20 percent was nonagricultural, including use for homes and gardens where more pesticide is often applied per square meter. Between 2005 and 2009, 2.2 kg of pesticide per hectare of arable land were applied in the United States, while rates of application were even higher in other countries such as China (10.3 kg/ha), an example of a country with extensive agricultural land use, and Colombia (15.3 kg/ha), where coffee is a valuable crop with heavy pressure from pests and therefore abundant use of pesticides can occur. Using data from 2001 to 2003, pests were estimated as causing between 26 and 40 percent losses in agricultural production for major crops around the world; surprisingly for the forty-year period before, although pesticide use increased over this time, these levels of crop loss had not changed significantly. Today, synthetic chemical pesticides are clearly the most commonly used method for pest control worldwide. Without crop protection, it is estimated that the losses to pests in agriculture would be approximately 60–86 percent. Therefore, crop protection is critically important and this need will only increase. By 2050, with a worldwide human population of approximately 9 billion, the worldwide demand for food will have doubled. In response to this increased demand for food, it is estimated that by 2050 global pesticide production will be 2.7 times greater than in 2000.

1.2 Why Consider Biological Alternatives for Pest Control?

Synthetic chemical pesticides are used so widely because they often work very well for controlling pests. However, pesticides are not always the optimal solution; sometimes they cannot control pests effectively for a variety of reasons. The major reasons that alternatives to synthetic chemical pesticides have been developed are presented below. In describing these scenarios, control of arthropods (e.g., insects and mites) will be used for examples although similar issues occur relative to the control of weeds and plant pathogens.

1.2.1 The Pesticide Treadmill

Although synthetic chemical pesticides are still the most widely used method for pest control, there are growing reasons to consider alternatives. Frequently, when pesticides are applied to control arthropods, naturally occurring controls are severely disrupted and natural enemies that normally live by consuming the pest are no longer abundant or even present. When this happens, if the target pest reinvades the treated area, there are no or few natural enemies present and the target pest population increases again unchecked, frequently to higher densities than were present initially (target pest resurgence) (Figure 1.2). Figure 1.3 shows the growth of an outbreak in a target pest, the California red scale, *Aonidiella aurantii*, as a result of regular spraying of low doses of DDT.

Since many natural enemies are often killed when broad-spectrum pesticides are applied, other organisms that had not been pests before the treatment can increase to densities that cause damage. This occurs because natural enemies that had previously maintained the nonpest populations at low densities are no longer present or abundant enough to provide control. This is known as a secondary pest outbreak (Figure 1.4). This scenario of a secondary pest outbreak can be demonstrated with increases in peach silver mites, *Aculus fockeui*, a species that was not a problem until the pyrethroid fluvalinate was applied to peach trees in Japan for control of other peach pests (including fruit borers, aphids, and spider mites). Before the application of fluvalinate, the peach silver

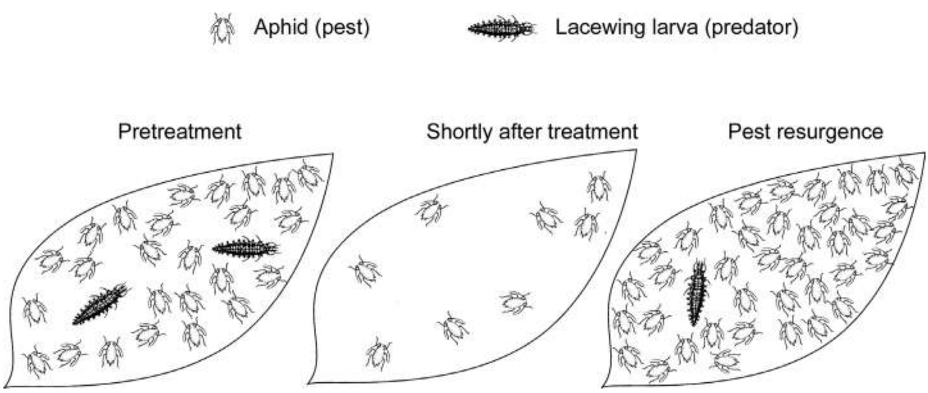

Figure 1.2 Target pest resurgence can occur when natural enemies are destroyed. Pesticides often kill a higher proportion of natural enemies than pests so that after application the pest can increase again rapidly (Flint & Gouveia, 2001).

mite population was naturally regulated, but after the pesticide treatment the predatory mite population was decimated and the peach silver mites were able to increase with little to stop them (Figure 1.5). New York State apple orchards provide an example of the diversity of secondary pests that can become problematic because of the application

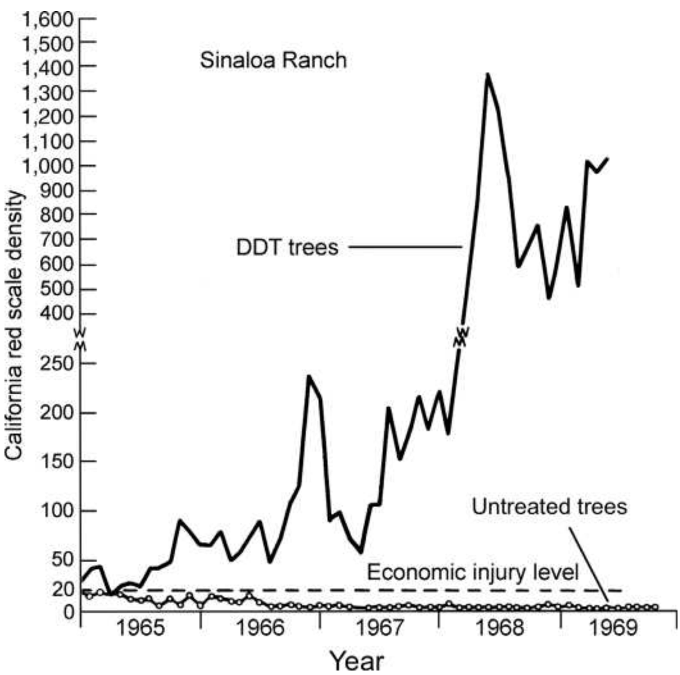

Figure 1.3 Increases in California red scale, *Aonidiella aurantii*, on citrus trees associated with monthly sprays of low doses of DDT, compared with nearby untreated trees under biological control (DeBach, 1974).

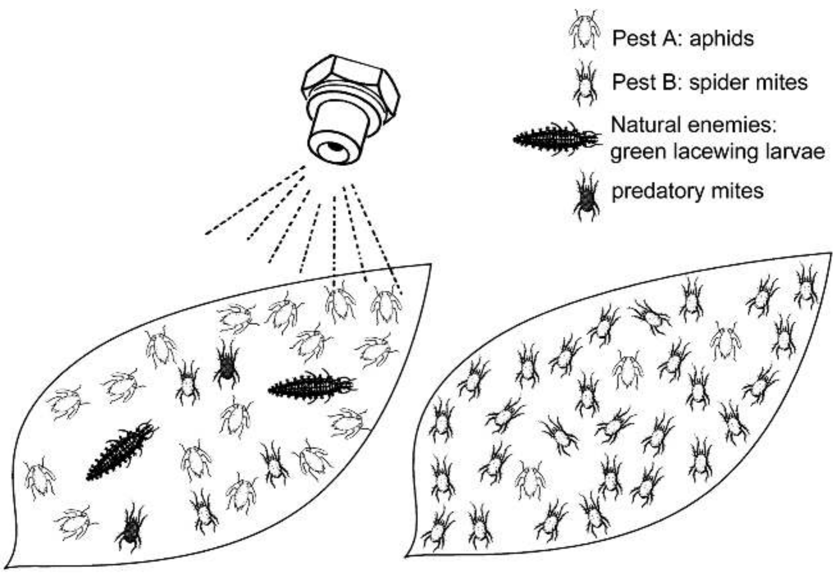

Figure 1.4 Secondary pest outbreaks occur when pesticide applications kill the natural enemies that have been controlling a species that has not been a pest. Without natural control, this species increases and can become a "secondary pest." For example, a pesticide applied to kill Pest A (aphids) killed aphids and their predators, the green lacewings, but also killed predatory mites, resulting in a secondary pest outbreak of Pest B (spider mites) previously kept at lower densities by predatory mites (Flint & Gouveia, 2001).

of broad-spectrum insecticides for control of multiple primary pests (Table 1.1). In this case, several different insect and mite species that normally cause no significant trouble for apple growers can multiply to pest densities causing economic losses because of severe reductions in the populations of their natural enemies. This example demonstrates that a diversity of problems can arise because of outbreaks of secondary pests when broad-spectrum pesticides kill natural enemies that are not the targets.

A third effect of extensive use of pesticides can be the evolution of pesticide resistance (Figure 1.6). Resistance often develops when a given pesticide is extremely, but not 100 percent, effective, causing the majority of the pest population to die after an application. The few individuals that remain are physiologically different and can tolerate the pesticide. This "new" strain of the pest that has been selected – that is, the survivor population that is resistant to the pesticide – can then increase even when the pesticide is reapplied. Overusing the pesticide in response to lack of pest control only hastens the occurrence of resistance throughout the pest population. Eventually, the pesticide in question has little or no effect on the pest and a different control strategy must be used. It is often assumed that when a new synthetic pesticide has been developed and is heavily applied, it will only be a matter of a few years before resistance

Table 1.1 Primary and secondary arthropod pests in apples in New York State.

Type of pest	Species	Type of damage
Primary pests	Codling moth (*Cydia pomonella*) Plum curculio (*Conotrachelus nenuphar*) Apple maggot (*Rhagoletis pomonella*) Obliquebanded leafroller (*Choristoneura rosaceana*)	For all primary pests, larvae (immature stages) damage or bore into developing apples
Secondary pests	San Jose scale (*Quadraspidiotus perniciosus*) European red mite (*Panonychus ulmi*) White apple leafhopper (*Typhlocyba pomaria*) Woolly apple aphid (*Eriosoma lanigerum*) Two-spotted spider mite (*Tetranychus urticae*)	For all secondary pests, apples are not directly damaged, but overall tree health can be affected

Source: A. Agnello (pers. comm.)

begins to develop in the target population. The length of time before resistance evolves depends on many factors, but resistance is always a threat to any pesticide.

While resistance to pesticides was first reported in 1914, it did not create major problems until the 1940s. Resistance to DDT was first seen in 1946 in house flies, *Musca domestica*, only 7 years after use began. By 1948, pesticide resistance was seen in 14 target species and by 2013 close to 600 species of arthropods displayed resistance to a variety of insecticidal active ingredients (Figure 1.7).

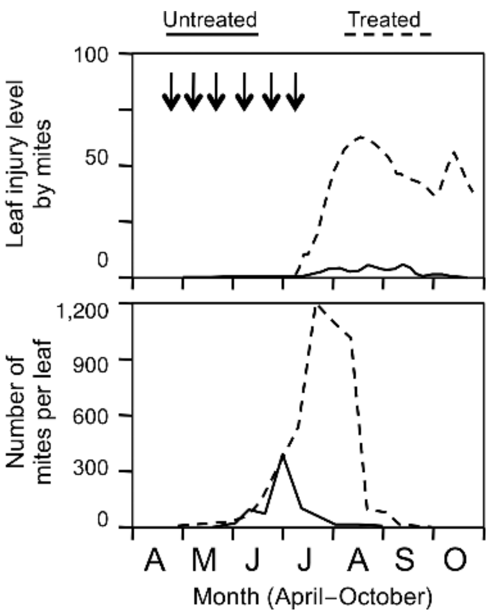

Figure 1.5 Effect of fluvalinate application on the population densities of peach silver mite in treated and untreated orchards with associated injury to peach leaves. Arrows indicate application times (based on Kondo & Hiramatsu, 1999).

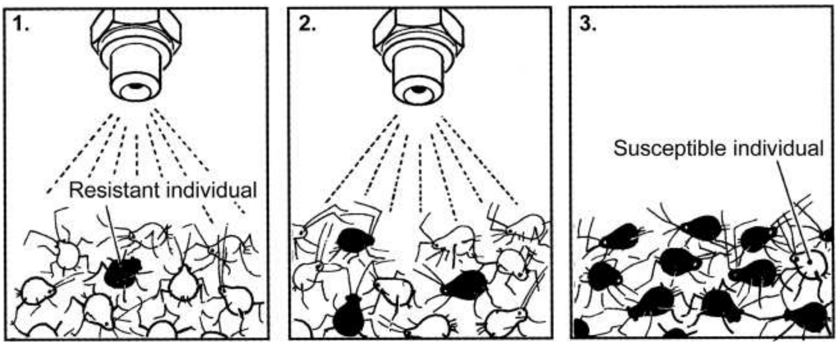

Figure 1.6 Pest populations can develop resistance to pesticides through natural selection. (1) When pesticides are applied, most individuals are killed, but a few are less susceptible and these remain. (2) The less susceptible individuals or their progeny are less likely to die with subsequent applications. (3) After repeated applications, the resistant or less susceptible individuals predominate and applying the same pesticide is no longer effective (Flint & Gouveia, 2001).

When resistance to a pesticide begins to develop, there is a characteristic series of events that often occur. First, growers may apply more of the pesticide, often not realizing that the lack of control is because of resistance. Next, growers might switch to a closely related pesticide, but once pests develop resistance to one pesticide in a pesticide class, they are often at least partially resistant to other similar pesticides. The

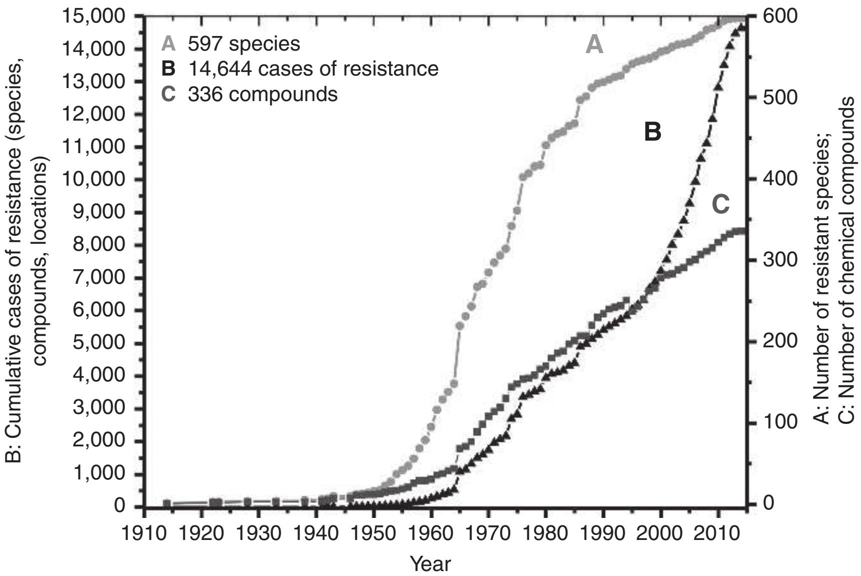

Figure 1.7 From 1945 to 2015, cumulative numbers in the United States of (A) arthropod species resistant to pesticides, (B) cases of resistance (by species, compound and location), and (C) chemical compounds with resistance documented (updated by D. Mota-Sanchez; data from Mota-Sanchez & Wise, 2017).

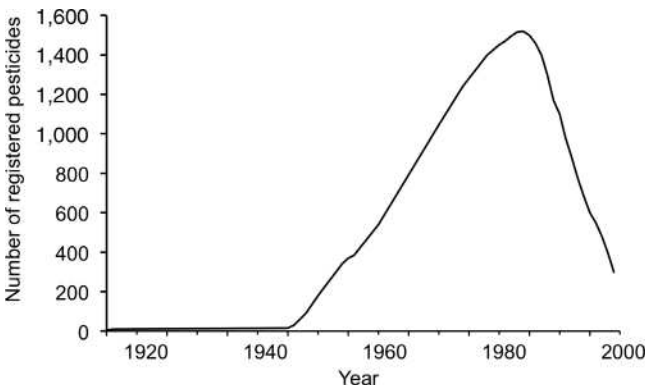

Figure 1.8 Total numbers of pesticides registered with the US Environmental Protection Agency from 1914 to 1999 (based on Mota-Sanchez et al., 2002).

grower might next choose a pesticide from another class of pesticides, for example switching from organophosphate insecticides to pyrethroids, under the assumption that the pest had acquired at least partial resistance to all organophosphates. However, pests can be resistant to several classes of pesticides at the same time so resistance can eventually develop to this second choice of control agent. To compound the troubles, frequently the alternative pesticide can be more costly. For example, with development of resistance to DDT, the organophosphate malathion was substituted at five times the cost. When resistance developed to malathion, fenitrothion, propoxur, or deltamethrin were often substituted by growers at 15–20 times the cost.

These three phenomena together (target pest resurgence, secondary pest outbreaks, and development of resistance in pest populations) have been termed the "pesticide treadmill." This can lead to increasing dependence on synthetic chemical pesticides, resulting in seemingly addictive use of this type of control.

1.2.2 Fewer Pesticides Are Available

As a result of the development of resistance to entire classes of pesticides, there is a constant demand for new types of pesticides, because the pesticides that previously were effective no longer provide adequate control. However, the costs of developing and registering new pesticides have increased over time. Since about 1970, there has been a significant slowdown in the rate of new pesticides being introduced to the market. It is estimated that 140,000 insecticidal compounds need to be screened to discover one successful compound and, once a compound has been identified, it can take about US$250 million and 8–12 years to develop and register a new material for application. In addition, owing to increasing regulation, some of the pesticides that have been available for many years are no longer legally available for application. For both of these reasons, in many countries there are fewer pesticides registered and thus available for use (see Figure 1.8 for the trend in the United States) and there are increasingly fewer new synthetic chemical pesticides for use (Figure 1.9). As one example, fumigation with

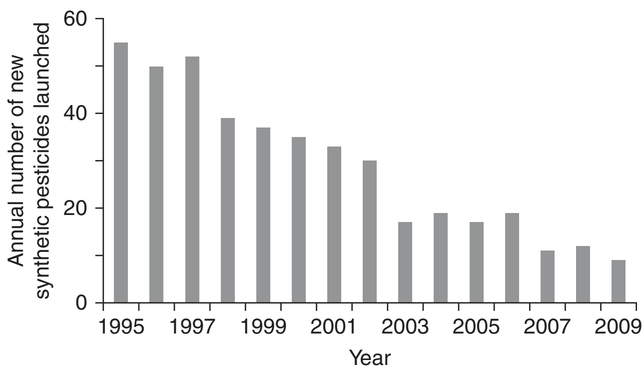

Figure 1.9 Annual numbers of new synthetic chemical pesticides for agriculture launched globally from 1995 to 2009 (based on Glare et al., 2012).

methyl bromide has been a mainstay for control of soil-borne and structural pathogens and pests as well as storage diseases of fruits and vegetables. However, use of this compound as a pesticide was phased out in most countries in the early 2000s, largely because of its role in ozone depletion. In its absence, alternative controls must be used. As another example, a moratorium was placed on use of three neonicotinoid insecticides by the European Union (EU) between 2013 and 2015 while the effects of these pesticides on wild bees were evaluated, with the future for use of these pesticides in the EU in question. In summary, there is a trend toward fewer synthetic chemical pesticide options as a result of increased resistance to existing insecticides and decreased development and registration of new compounds.

1.2.3 Synthetic Chemical Pesticides Aren't Always the Answer

There are some situations for which chemical pesticides are not the most appropriate choice for controlling pests. One example would be introduced exotic organisms that become pests; it has been estimated that 50,000 exotic organisms have been introduced to the United States alone and those having an impact of some kind are referred to as invasive species. In fact, invasive species are now considered a major problem worldwide as a result of the increasing human population frequently moving organisms around the globe and thereby altering ecosystems at an increasingly alarming rate. Many invaders can become pestiferous because of the fact that they are no longer associated with the natural enemies with which they coevolved. Among pests in agriculture, approximately 20–40 percent have been introduced from elsewhere. While most introduced organisms are accidental introductions, a small percentage of these were purposeful introductions such as crop plants and honey bees (*Apis mellifera*). Some were purposeful introductions with unexpected side effects, for example, the weed kudzu (*Pueraria* species) that was introduced to the southeastern United States to control erosion became established and then spread rampantly through much of the region, becoming a problematic weed. Introduced organisms are not always identified quickly,