Chapter 1

The IPM paradigm: concepts, strategies and tactics

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Pests compete with humans for food, fiber and shelter and may be found within a broad assemblage of organisms that includes insects, plant pathogens and weeds. Some insect pests serve as vectors of diseases caused by bacteria, filarial nematodes, protozoans and viruses. Densities of many pests are regulated by density-independent factors, particularly under fluctuating environmental extremes (e.g. temperature, precipitation). Biotic components within a pest's life system also may serve as important population regulation factors, such as interactions with predators and parasitoids. Some ecologists have theorized that competition (interspecific and/or intraspecific) for resources ultimately limits the densities and distributions of organisms, including those that are anthropocentrically categorized as pests.

1.1 Historical perspectives

Humans have been in direct competition with a myriad of pests from our ancestral beginnings. Competition with pests for food intensified when humans began to cultivate plants and domesticate animals at the beginnings of agriculture, 10 000 to 16 000 years ago (Perkins, 2002; Thacker, 2002; Bird, 2003). As humans became more competent in producing crops used for food and fiber, human densities began to increase and were organized in larger groupings such as villages. This increased concentration of humans in close proximity to their livestock is believed to have facilitated the mutation and spread of diseases across species in some instances. The earliest attempts at agricultural pest control were likely very direct and included handpicking and crushing insects, pulling or cutting weeds and discarding rotting food sources. Some pest control activities were inadvertent and included rotation or movement of crops (primarily planting crops in more fertile areas) and selection of plants for seed that had the greatest yields for sowing the following growing season.

The reasoned use of pesticides is centuries old (2500 BC) dating back to when sulfur was directed at the control of mites and insects (Bird, 2003; Kogan & Prokopy, 2003). The ancient Egyptians also are credited with the use of compounds extracted from plants to aid in the control of insects and approximately 2000 years ago, Pliny listed arsenic and olive oil as pesticides. (Thacker, 2002). In AD 307, biological control was utilized in Chinese citrus orchards (Bird, 2003) and in AD 1100 soap was being used as an insecticide in China (Kogan & Prokopy, 2003). Perkins (2002) asserted that pest control began to transform significantly about four centuries ago:

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About 400 years ago in Western Europe, a set of transformations completely changed economic life and, with it, pest control. New machines and new ways of making metals enabled industrialization. The new industrial processes were themselves linked to a new philosophy of nature, in which humans learned to manipulate natural processes more powerfully, particularly energy resources.

Thacker (2002) provides a list of insecticidal plants and their active compounds discovered by Europeans following the sixteenth century: sabadilla (*Sabadilla officinarum*) (*c*. 1500s); nicotine (*Nicotiana tabacum*) (late 1500s); quassin (*Quassia amara*) (late 1700s); heliopsin (*Heliopsis longipes*) (early 1800s); ryanodine (*Ryania speciosa*) (1940s); naphthoquinones (*Calceolaria andina*) (1990s); and derris (*Derris chinensis*) (mid-1990s). Many of these insecticidal plants were already being used for pest control purposes by native cultures prior to European exploration of the New World (Thacker, 2002).

In the late 1800s, inorganic compounds were discovered that offered impressive insecticidal and fungicidal properties. In 1865, the Colorado potato beetle (*Leptinotarsa decemlineata*) was controlled by Paris green (cupric acetoarsenite), the first synthetic insecticide (Metcalf, 1994). Prior to the introduction of potatoes by settlers (1850s) into the western plains of the USA, this beetle fed primarily on the buffalo burr (*Solanum rostratum*). This insect soon found potatoes to be an excellent host. Lead arsenate replaced Paris green and was used extensively for Colorado potato beetle control until DDT became more readily available. Plant pathologists also determined (1880s) that synthetic compounds such as Bordeaux mixture (copper sulfate and hydrated lime) reduced the severity of downy mildew in grape vineyards (Perkins, 2002). In subsequent years, other metabolic inhibitory fungicidal compounds were utilized, such as those containing mercury. Weed control was largely dependent upon plowing and hoeing until the introduction (early 1940s) of 2,4-dichlorophenoxy acetic acid (Perkins, 2002). In addition to these early chemical approaches to pest control, farmers relied upon their rudimentary knowledge (Webster, 1913) of pest life cycles and the use of cultural tactics to limit crop losses.

In 1939, the insecticidal properties of DDT (dichlorodiphenyltrichloroethane) were discovered by Paul Herman Müeller, a scientist with the Geigy Chemical Company. Most entomologists view this development as the beginning of the modern insecticide era. The pest control benefits of this new insecticide were regarded initially as miraculous. Some referred to DDT as the "wonder" insecticide (Metcalf, 1994). During World War II, DDT was used extensively to prevent epidemics of several insect-vectored diseases such as yellow fever, typhus, elephantiasis and malaria. The use of DDT for insect control in the production of crops, protection of livestock, in forestry and in urban and public health arenas soared in the late 1940s and 1950s. In 1946, DDT-resistant strains of the house fly (*Musca domestica*) were reported in Sweden and Denmark (Metcalf, 1994). Despite this "chink" in the armor of DDT, the promise of chemicals to deliver economical and effective pest control (including that of plant diseases and weeds) heralded in an atmosphere characterized by an over-reliance on pesticides throughout the 1950s and 1960s. This over-reliance on insecticides soon led to many significant ecological backlashes such as insecticide resistance, concentration of chlorinated hydrocarbon insecticides in the food chain, significant declines in densities of natural enemy (predators and parasitoids) populations, secondary outbreaks of pests, resurgence of primary pests and unwanted insecticide residues on fruits and vegetables. Critics of this over-reliance on pesticides argued that basic biological research on pest ecology and alternative management strategies were being ignored. Entomologists engaged in biological control efforts in California, cotton production in North and South America and production of fruit in orchard systems (Canada, Europe and the USA) were among the first to recognize many of the acute ecological problems associated with indiscriminate pesticide use (Kogan, 1998).

1.2 Early conceptual efforts in IPM development

In 1959, University of California entomologists at Berkeley, Vernon Stern, Ray Smith, Robert van den Bosch and Kenneth Hagen, published a seminal paper entitled "The Integration of Chemical and

Biological Control of the Spotted Alfalfa Aphid." In this paper, they offered the following statement concerning the integrated control concept:

> Whatever the reasons for our increased pest problems, it is becoming more and more evident that an integrated approach, utilizing both biological and chemical control, must be developed in many of our pest problems if we are to rectify the mistakes of the past and avoid similar ones in the future.

Many terms and concepts, now well known by entomologists, plant pathologists, weed scientists and IPM practitioners, were defined by these authors such as economic threshold, economic injury level and general equilibrium position. The following definitions are provided from Stern *et al.* (1959):

economic injury level	The lowest population density that will cause economic damage.
economic threshold	The density at which control measures should be determined to prevent an increasing pest population from reaching the economic injury level
general equilibrium position	The average density of a population over a period of time (usually lengthy) in the absence of permanent environmental change

Integrated control was defined as *applied pest control which combines and integrates biological and chemical control* and employed the use of economic thresholds to determine when chemical control should be utilized to prevent pests from reaching the economic injury level. The integrated control concept has evolved into the IPM concept that includes insects, plant pathogens, weeds and vertebrate pests. Since the initial tenets of the integrated control concept were developed in response to insect pests, not all of the early basics fit well with regard to the practical management of weeds, plant pathogens and vertebrate pests. Knake & Downs (1979) indicated that IPM should be an interdisciplinary approach rather than simply combining various control options within one discipline: "Weeds harbor insects and diseases, diseases may kill insects and weeds, and insects can be used to control other insects and weeds." Ford (1979) described three threshold types for plant pathology IPM programs: (1) a threshold addressing detection, (2) a threshold for prevention due to zero injury tolerance and (3) the more standardized economic injury threshold. Integrated vertebrate pest control applies ecology and only supports destruction of individual vertebrates as a last option to address animal damage (Timm, 1979). The impact of pest management implementation requires careful examination of potential benefits, costs and risks. While increased producer productivity is often considered a benefit, if it is obtained at a high environmental cost, the true economic impact may be obscured (Carlson & Castle, 1972). Higley & Wintersteen (1992) suggested that the traditional use of economic thresholds and injury levels are insufficient in estimating the hidden environmental externalities associated with insecticide use.

Some debate persisted among academics throughout the 1960s and into the 1980s regarding the perceived differences between "pest management" and "integrated control" (Kogan, 1998). Smith & Reynolds (1966) presented the concept of integrated pest control as a multifaceted, flexible, evolving system that blends and harmonizes control practices in an organized way. They believed the system must integrate all control procedures and production practices into an ecologically based system approach aimed at producing high quality products in a profitable manner. While this debate ensued, Rachel Carson published *Silent Spring* in 1962. This book galvanized sentiment among the general public against the abuses of pesticide applications. She was criticized by some for her use of emotionally charged passages such as (from Chapter 3, "Elixirs of Death"):

> For the first time in the history of the world, every human being is now subjected to contact with dangerous chemicals, from the moment of conception until death. In the less than two decades of their use, the synthetic pesticides have been so thoroughly distributed throughout the animate and inanimate world that they occur virtually everywhere.

She is given deserved credit for inspiring a generation of environmentalists and forcing the scientific community and governmental agencies

to more closely scrutinize pesticide use and registration requirements. Eight years after *Silent Spring* was published, the US Congress mandated that the administration and enforcement of the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) be transferred from the US Department of Agriculture (USDA) to a newly created federal entity, the US Environmental Protection Agency (EPA). The passage of FIFRA amendments over the past 30 years has resulted in policies aimed at reducing environmental and human health and safety risks that are linked with pesticide use (Gray, 2002). Kogan (1998) indicated the following with respect to the popularization of IPM:

> Not until 1972, however, were "integrated pest management" and its acronym IPM incorporated into the English literature and accepted by the scientific community. A February 1972 message from President Nixon to the US Congress, transmitting a program for environmental protection, included a paragraph on IPM.

Kogan (1998) further added that broad agreement had by then been reached on several key points regarding IPM:

> (1) **integration** meant the harmonious use of multiple methods to control single pests as well as the impacts of multiple pests; (2) **pests** were any organism detrimental to humans, including invertebrate and vertebrate animals, pathogens, and weeds; (3) IPM was a multidisciplinary endeavor; and (4) **management** referred to a set of decision rules based on ecological principles and economic and social considerations.

Some continue to debate the definition of IPM; however, the key components of this concept can be found in these four elements. More recently, in response to a national review of the federally supported US IPM Program (US General Accounting Office, 2001), and considerable stakeholder input, the USDA developed the "IPM Road Map" (see Chapter 37) with the ultimate objective of increasing IPM implementation by practitioners such as "land managers, growers, structural pest managers, and public and wildlife health officials." The IPM Road Map (2003) offers a definition of IPM that includes the historical elements of IPM reviewed by Kogan (1998), and in many ways extends the concept to focus on reducing the risks of economic and environmental losses. Within the IPM Road Map (May, 2004 version) IPM is defined as:

> . . . a long-standing, science-based, decision-making process that identifies and reduces risks from pests and pest management related strategies. It coordinates the use of pest biology, environmental information, and available technology to prevent unacceptable levels of pest damage by the most economical means, while posing the least possible risk to people, property, resources, and the environment. IPM provides an effective strategy for managing pests in all arenas from developed residential and public areas to wild lands. IPM serves as an umbrella to provide an effective, all encompassing, low-risk approach to protect resources and people from pests.

1.3 Kinds of pests

The selection of a strategy and components of an IPM program are largely influenced by the status of a pest in relationship to its host. Four pest types are commonly recognized by IPM practitioners: (1) *subeconomic*, (2) *occasional*, (3) *perennial* and (4) *severe* (Pedigo & Rice, 2006).

(1) The general equilibrium position of a *subeconomic pest* is always below the economic injury level, even during its highest population peaks. An insect in this category may cause direct losses but if the host (crop) values are modest, and the pest densities are always low, then it is not appropriate to initiate control practices whose costs exceed the value of host damage.

(2) The general equilibrium position of an *occasional pest* is nearly always below the economic injury level but occasionally population peaks exceed this level. The occasional pest is a very common type of pest. It may be present on or near a host nearly every year, but only sporadically does it cause economic damage.

(3) The general equilibrium position of a *perennial pest* is below the economic injury level but peak populations occur with such frequency that economic damage usually occurs yearly.

(4) A *severe pest* has a general equilibrium position that is always above the economic injury level so that when they occur in or on a host, economic damage is always the end result. As might be expected, perennial and severe pests cause the most serious damage and difficult challenges in an IPM program.

1.4 Pest management strategies and tactics

A pest management strategy is the total approach to eliminate or reduce a real or perceived pest problem. The development of a particular strategy will be greatly influenced by the biology and ecology of the pest and its interaction with a host or environment. The goal should be to reduce pest status when addressing problems using pest management. Because both the pest and host determine pest status, modification of either or both of these may be emphasized in a management program. Therefore, four types of strategies (Pedigo & Rice, 2006) could be developed based on pest characteristics and economics of management: (1) do nothing, (2) reduce pest numbers, (3) reduce host susceptibility to pest injury and (4) combine reduced pest populations with reduced host susceptibility. Once a pest management strategy has been developed, the methods of implementing the strategy can be chosen. These methods are called pest management tactics, and several tactics may be used to implement a management strategy.

1.4.1 Do-nothing strategy

All pest injury does not cause an economic loss to a host. Many hosts, especially plants and occasionally animals, are able to tolerate small amounts of injury without suffering economic damage. It is not uncommon for trivial insect injury to be mistaken for economically significant injury. This is most likely to occur when the pest population density is not considered in relationship to an economic threshold. If the pest density is below the economic threshold, then the do-nothing strategy is the correct approach; otherwise money would be expended on control that would not result in a net benefit. The do-nothing strategy is frequently used when insects cause indirect injury to a host, or when a successful pest management program reduces the pest population and only surveillance of the remaining population is necessary. No tactics are used in the do-nothing strategy, but this does not imply that no effort is necessary or that pest suppression is not occurring. Sampling of the pest population is required to determine that the do-nothing strategy is the appropriate response, and environmental influences may reduce the population, resulting in pest suppression.

1.4.2 Reduce pest numbers

Reducing pest densities to alleviate or prevent problems is probably the most frequently used strategy in pest management. This strategy is often employed in a therapeutic manner when populations reach the economic threshold or in a preventive manner based on historical problems (Pedigo & Rice, 2006). Two objectives may be desirable in attempting to reduce pest densities. If the pest's long-term average density, or general equilibrium position, is low compared with the economic threshold, then the best approach would be to diminish the population peaks of the pest. This action would not appreciably change the pest's general equilibrium position, but it should prevent damage from occurring during pest outbreaks. If, however, the pest population's general equilibrium position is near or above the economic threshold, then the general equilibrium position must be lowered so that the highest peak populations never reach the economic threshold. This may be done by either reducing the carrying capacity of the environment, or by reducing the inherited reproductive and/or survival potential of the population (Pedigo & Rice, 2006). There are many tactics that can be used to reduce pest numbers including resistant hosts, insecticides, pheromones, mechanical trapping, natural enemies, insect growth regulators, release of sterilized insects and modification of the environment.

1.4.3 Reduce host susceptibility to pest injury

One of the most environmentally compatible and effective strategies is to reduce host susceptibility to pest injury. This strategy does not modify the pest population; instead the host or host's

relationship and interaction with the pest is changed to make it less susceptible to a potentially damaging pest population. A common form of this strategy is where plant cultivars or animal breeds are developed with a type of resistance, known as tolerance, which provides greater impunity to a pest than a similar plant or animal without the tolerance. The tolerance expressed by a plant or animal does not reduce the attacking pest population, but the injury caused by the pests has less of a detrimental affect on the host (i.e. yield loss in plants or weight loss in animals) than it does on a similar host without the tolerance. The other component to this strategy, ecological modification of factors that influence the distribution or abundance of a pest, also can reduce host susceptibility. Examples of this strategy would be reducing livestock exposure to a pest insect by moving them from an outdoor environment to an indoor facility or adjusting a crop planting date to create an asynchrony between a pest and a susceptible plant stage.

1.4.4 Combine reduced pest populations with reduced host susceptibility

A strategy that combines the objectives of the previous strategies is a logical step in the development of a pest management program. A multifaceted approach is more likely to produce greater consistency than a single strategy using a single tactic. Experience has shown that a single strategy is more likely to fail when either, slowly or quickly, a single tactic approach falters. With the multifaceted approach, if one tactic fails, then other tactics operate to help modulate losses. The use of multiple strategies and tactics is the basic principle in developing an IPM program.

1.5 Funding IPM research and implementation

Since the early 1970s, the USDA, the EPA and the National Science Foundation (NSF) have been the primary governmental agencies in the USA that have provided competitive and formula-based funding for research and extension IPM programs. The majority of these IPM research and extension programs are conducted by investigators located at land-grant universities (Morrill Land-Grant Acts, 1862, 1890). Two of the most visible and comprehensive IPM pilot efforts included the Huffaker (1972–1979, $US 13 million in funding, EPA, NSF, USDA) and Adkisson (1979–1984, $US 15 million in funding, EPA, USDA) projects (Allen & Rajotte, 1990). The Huffaker Project concentrated on the development of IPM tactics for insect pests in cotton, soybeans, alfalfa, citrus fruits, and pome and stone fruits. The Adkisson Project expanded its range of targeted pests to include diseases, insects and weeds in alfalfa, apples, cotton and soybeans. In 1978, a USDA report from the Extension Committee on Organization and Policy recommended that $US 58 million be spent on extension IPM programs. This goal was never achieved and federal funding for extension IPM programs began to falter reaching approximately $US 7.0 million in the early 1980s (Allen & Rajotte, 1990). By 2006, federal formula funds [Smith-Lever 3(d)] allocated across the USA for extension IPM programs had risen to a modest $US 9.86 million, or roughly $US 200 000 per state. Reasons are diverse for the weakening political support and funding for new and large-scale IPM initiatives in the USA (Gray, 1995). These reasons include the perception that implementation of IPM would lead to greater overall reductions in pesticide use than has occurred in some cropping systems, political support for "older" programs often wanes over time in lieu of new initiatives, continued difficulty in quantifying successes and impact of IPM implementation, struggles of IPM leadership to clearly articulate the goals of IPM implementation, and increasing popularity of organic production practices.

Funding of IPM research and implementation programs in developing countries is increasingly important as food production and environmental concerns intensify in many densely populated areas around the globe. Some key organizations and programs that fund and promote these IPM efforts include: Food and Agriculture Organization of the United Nations (FAO), United Nations Environment Program (UNEP) and the United Nations Development Program (UNDP). In 1995, the Global IPM Facility was established and is housed in FAO Headquarters in Rome, Italy. Co-sponsors of the Facility include FAO, UNEP,

UNDP and the World Bank (Stemerding & Nacro, 2003). It was hoped that the Facility would ultimately result in more lending operations that would support IPM implementation. Thus far, the impact of the Global IPM Facility has been assessed as "mixed" (Schillhorn van Veen, 2003). Other key organizations that fund and promote IPM globally include the Integrated Pest Management Collaborative Research Support Program (IPM CRSP). This program was started in 1993 with the financial assistance of the US Agency for International Development (USAID). Current sites include: Albania, Bangladesh, Ecuador, Guatemala, Jamaica, Mali, Philippines and Uganda. Several USA institutions (Virginia Tech, Ohio State University, Purdue University) provide personnel who collaborate with scientists at the host institutions. Successful IPM programs that have been developed through this effort include: rice and vegetable cropping systems in the Philippines, maize and bean cropping systems in Africa, horticultural export crops in Latin America and sweet potato production in the Caribbean (Gebrekidan, 2003). Significant international contributions in host plant resistance to a variety of pests in crops have been achieved through support of the Consultative Group on International Agricultural Research (CGIAR) centers. These centers support the implementation of systemwide programs on IPM in several international "target zones" such as Africa, Asia and Latin America (James *et al.*, 2003).

1.6 Measuring IPM implementation

Assessing the level of IPM implementation has historically presented a challenge to policy makers, governmental agencies and scientists (Wearing, 1988). In an era of increasing pressure to ensure accountability, continued governmental support of IPM programs (research and extension) is contingent upon documenting increasing levels of IPM adoption and proving impact (economic, environmental and human health and safety benefits). Not all scientists, policy makers or practitioners of IPM agree that the primary goal of IPM is to reduce pesticide use (Gray, 1995; Ratcliffe & Gray, 2004). The US Council on Environmental Quality (1972) described IPM as "an approach that employs a combination of techniques to control the wide variety of potential pests that may threaten crops." It suggests numerous economic pests can be managed by "maximum reliance" on natural pest controls with the incorporation of key elements including cultural methods, pest-specific diseases, resistant crop varieties, sterile insects and attractants together with the use of biological control and reduced risk, species-specific chemical controls as part of an IPM program. Risk management and the fear of crop loss is often overemphasized, but coupled with the lack of implementation incentives many producers choose to only adopt limited aspects of IPM rather than a whole system approach (US Council on Environmental Quality, 1972).

In September 1993 (US Congress, 1993) the Clinton Administration set a goal for 75 percent implementation of IPM practices, by 2000, on managed agricultural areas in the USA. A National Agricultural Statistics Service (2001) report indicated that by 2000, IPM adoption levels for many crops had met or exceeded this goal. However, in 2001, the United States General Accounting Office (GAO) published a document that was critical of the coordination and management of federal IPM efforts (across more than a dozen federal agencies). In addition, some criticism within the GAO report was directed at the lack of measurement and evaluation tools (environmental and economic) for assessing the level of IPM implementation. Since 2000, four regional IPM Centers within the USA have sought to improve the coordination of IPM implementation efforts utilizing a National Road Map for IPM (first articulated at the 4th National IPM Symposium, Indianapolis, IN, April 2003; see Chapter 37) as a blueprint (Ratcliffe & Gray, 2004). Bajwa & Kogan (2003) provide a very good assessment of IPM adoption in Africa, Americas (other than USA), Asia, Australia, Europe and the USA for many crops. The percentage of farmers who have adopted IPM practices is very high in many cases, such as: pear production in Belgium (98 percent), cotton production in Australia (90 percent), pome fruits in British Columbia (75 percent), and sugarcane production in

Colombia (100 percent). Despite these advances in IPM implementation, pesticide usage has increased in many developing countries throughout the 1990s and remains the exclusive tactic to control pests. Bajwa & Kogan (2003) remind us that "IPM is a tangible reality in some privileged regions of the world, but still remains a distant dream for many others."

1.7 Examples of successful implementation of IPM

1.7.1 Ecological management of environment: push–pull polycropping in Africa

Push–pull strategies use a combination of behavior-modifying stimuli to manipulate the distribution and abundance of pest or beneficial insects in pest management with the goal of pest reduction on the protected host or resource (Cook *et al*., 2007). Pests are repelled or deterred away from the resource (push) by using stimuli that mask host apparency or are deterrent or repellant. Pests are simultaneously attracted (pull), using highly apparent and attractive stimuli, such as trap crops, where they are concentrated, facilitating their elimination (Cook *et al*., 2007).

The most successful push–pull strategy was developed for subsistence farmers in east Africa. Maize (*Zea mays*) and sorghum (*Sorghum bicolor*) two principal foods in east Africa, are attacked by lepidopteran stem borers, e.g. *Busseola fuscus*, *Chilo partellus*, *Eldana saccharina* and *Sesamia calamistis*, that cause 10–50 percent yield losses (Cook *et al*., 2007). Farmers combine the use of intercrops and trap crops, using plants that are appropriate for the farmers and exploit natural enemies. Stem borers are repelled from the maize and sorghum by non-hosts such as greenleaf desmodium (*Desmodium intortum*), silverleaf desmodium (*Desmodium uncinatum*) and molasses grass (*Melinis minutiflora*), which are interplanted with the maize or sorghum (the push). Around the field edges are planted trap crops, mostly Napier grass (*Pennisetum purpureum*) and Sudan grass (*Sorghum vulgare sudanense*), which attract and concentrate the pests (the pull). These grasses have a dual purpose as they are also used as forage for livestock. Molasses grass, as an intercrop, reduces stem borer populations by producing stem borer repellent volatiles; it also increases parasitism by a parasitoid wasp. *Desmodium* also produces similar repellent volatiles; but also produces sesquiterpenes that suppress the parasitic African witchweed (*Striga hermonthica*), a major yield constraint of cropland in east Africa. The desmodium compounds stimulate germination of witchweed seeds and subsequent mortality of the seedlings. The push–pull strategy has contributed to increased grain yields and livestock production in east Africa, resulting in significant impact on food security (Cook *et al*., 2007).

1.7.2 Biological control: prickly pear cactus and cactus moths in Australia

Prickly pears, or prickly pear cactus (*Opuntia* spp.), are native to the Americas but have become serious invasive weeds in suitable habitats around the world. Around 1840, cuttings of prickly pears were brought to Queensland, Australia for use as a hedge around fields and homesteads, as a botanical curiosity, and for production of cochineal – a dark reddish dye produced by scale insects that feed on the plant. Livestock and native birds quickly spread prickly pear seeds across overgrazed grasslands, where competition was reduced during droughts, whereas during heavy rainfall, broken pieces of prickly pears were carried into the interior on westward-flowing rivers (DeFelice, 2004). The climate and soil of eastern Australia was ideal for prickly pear and the weed quickly spread. Attempts were made by farmers and ranchers in the 1880s to control the weed, but were without success. In 1893, it was declared a noxious weed in Queensland.

By 1913, prickly pear was estimated to cover 1.4 million ha with dense infestations and another 4.9 million ha with scattered infestations. By 1926, the prickly pear had infested 24 million ha in Queensland and New South Wales and was spreading at the rate of 1 million ha annually (DeFelice, 2004). Attempts at controlling the prickly pear using mechanical, chemical and cultural methods completely failed to stop the spread of the weed, mostly because control was poorly supported and many government policies only conspired to worsen the problem (DeFelice, 2004).

The infestation was so dense the 12 million ha were rendered useless, resulting in worthless grazing land and the abandonment of many farms and homesteads.

In 1927, hope appeared in the form of an imported parasitic insect from South America – the cactus moth (*Cactoblastis cactorum*). This insect was evaluated and confirmed to only feed on prickly pear. Over 220 million eggs were reared and distributed and three years later 200 000 ha of prickly pear were destroyed. The insect rapidly spread and by the end of 1931, millions of hectares of prickly pears were a mass of rotting vegetation (DeFelice, 2004). Land that had been useless for decades was cleared and restored to rangelands and agricultural production. The prickly pear experience in Australia was one of the most frightening cases in history of ecological destruction by an invasive plant and also one of the most successful biological control campaigns ever mounted against a pest.

1.7.3 Sterile insect technique: screwworm eradication in North and Central America

The classic achievement of success with the sterile insect technique was the eradication of the screwworm (*Cochliomyia hominivorax*) from the USA, Mexico and Central America. The screwworm is an obligate parasite of livestock and has occasionally attacked humans. The adult fly lays up to 450 eggs in open wounds where the larvae feed on tissues and enlarge the wound (Krafsur *et al.*, 1987). Feeding by the larvae attracts other flies to oviposit in the wound, thereby aggravating the damage to the animal. Heavily parasitized livestock may be killed within 10 days. Historical livestock losses to this pest were astronomical. Prior to the sterile release program, losses were estimated at $US 70–100 million annually across the southern USA from Florida to California. A severe pest outbreak occurred in this region in 1935, with 1.2 million cases of infestation and 180 000 livestock deaths.

The sterile insect technique involves the intentional release of large numbers of sterilized insects to compete with wild insects for mates (Krafsur *et al.*, 1987). The sterile insect technique with screwworms involves the mass rearing of larvae on a specialized liquefied diet of bovine blood and powdered egg. The pupae are collected from the rearing containers and at five days of age are irradiated with cesium. Female flies irradiated with this process fail to undergo vitellogenesis and therefore do not deposit eggs. Male flies likewise are sterilized and when they mate with a wild-type female, no viable eggs are produced.

The concept of the sterile insect technique was put to the test in a pilot program on Sanibel Island, Florida and produced positive results. A larger test was initiated in 1954 on Curaçao, an 444-km^2 island off the coast of Venezuela, where 400 sterilized males per 2.6 km^2 were released for three months. The effort resulted in the complete eradication of the screwworm from the island and demonstrated the potential of the technique. The technique was then applied to livestock in Florida and southern Georgia and Alabama in 1958. More than 2000 million sterilized flies were released from airplanes during an 18-month period, resulting in complete eradication from the region. The program was then moved to southwestern USA in the early 1960s where sterile flies were released along the international border with Mexico. This resulted in a fly-free zone nearly 3200 km long and 500 to 800 km deep which prevented the flies from moving north into the USA. Fly infestation reports dropped from more than 50 000 in 1962 to 150 by 1970. Unfortunately, infestations did not remain low so a cooperative agreement between the USA and Mexican governments worked together to push the screwworm further south in Mexico. By 1986, Mexico was declared free of screwworm. The fly-free zone was continually moved south, eradicating the pest from numerous Central American countries. A fly-free barrier is currently maintained in Panama to prevent reinfestations from South America. In 1992, Raymond Bushland and Edward Knipling received the World Food Prize for their collaborative achievements in developing the sterile insect technique for eradicating or suppressing the threat posed by pests to crops and livestock.

1.7.4 Transgenic plants: control of European corn borer in North America

The European corn borer (*Ostrinia nubilalis*) has been considered by some (Ostlie *et al.*, 1997) to be the most damaging pest of maize in North

America with damage and control costs exceeding $US 1000 million during the early to mid-1990s. Insecticides were occasionally used by growers to prevent stalk tunneling, kernel damage and fallen ears in maize but often they were reluctant to embrace chemical control (Rice & Ostlie, 1997). Reasons for reluctance included the fact that larval damage was hidden, large infestations are unpredictable, fields had to be scouted multiple times requiring time and skill, insecticides were expensive and raised environmental and health concerns and benefits of insecticide control were uncertain. These concerns paved the way for a novel way of managing this pest through the use of transgenic plants.

In 1996, Mycogen Seeds and Novartis Seeds introduced the first commercial *Bt* maize hybrids. The *Bt* hybrids were genetically transformed to express a gene from the soil bacterium, *Bacillus thuringiensis*, which produces a protein that is toxic to European corn borer larvae. Most larvae die after taking only a few bites of maize leaf tissue. Consequently, *Bt* maize provides extremely high levels of larval mortality resulting in exceptional yield protection even during heavy infestations of European corn borer (Ostlie *et al.*, 1997). In 2005, approximately 35 percent of the maize hectares were planted to a corn borer resistant transgenic hybrid with the result being that during the past ten years, the European corn borer has had a steady decline in the severity of populations, thereby leading some to conclude that the insect has become a secondary pest (Gray, 2006). An additional effect was that the percent of farmers who decreased their insecticide use doubled during the first three years of planting a transgenic maize hybrid resulting in less broad-spectrum insecticide applied to the fields (Pilcher *et al.*, 2002). Maize growers perceive that less exposure to insecticides and less insecticide in the environment are the two primary benefits of planting transgenic maize hybrids (Wilson *et al.*, 2005). The success of commercial transgenic *Bt* maize has lead to the development of triple-stacked hybrids that may express a protein for corn borers, a different protein specific for corn rootworms (*Diabrotica* spp.) and resistance to herbicides.

1.7.5 Insect growth regulators: termite control in North America

Termites are destructive pests of wooden structures and the latest industry estimates place the annual cost of damage and treatment at $US 5000 million worldwide (National Pest Management Association, 2005). Termite control generally consists of five types of treatment programs: liquid termiticides, bait systems, wood preservatives, mechanical barriers and biological termiticides (Hu, 2005). Each type of program has its advantages and disadvantages, but the bait system is the most novel as it uses an insect growth regulator to control the termite colony.

The bait system is a relatively new tool for termite control. Instead of applying a chemical barrier designed to exclude termites from a wooden structure, termites are offered food in the form of baits (Hu *et al.*, 2001). Treatment baits have two components: a termite food source, such as a block of wood in the soil, and a slow-acting termiticide, often an insect growth regulator. The insect growth regulator (diflubenzuron, hexaflumuron or noviflumuron) is a slow-acting, non-repellent toxicant that prevents the formation of chitin in the insect cuticle. Termites feeding on the bait are not killed immediately, but through colony recruitment when worker termites find the bait the insect growth regulator is passed to other colony members, ultimately leading to decline or perhaps elimination of the colony. The advantage of baiting is that the system is non-intrusive, consumer friendly, safer than most of the soil-applied insecticides, specifically targets termites and dramatically reduces the amount of chemical needed to protect a structure. However, a disadvantage is that the process may take weeks or months to knock down termite populations.

1.8 IPM within a transgenic era

In 1996, transgenic crops were commercialized on a limited basis in the USA for the first time. In ten years, the use of transgenic crops has seemingly transformed the IPM paradigm, particularly in the major field crops arenas. The primary transgenic tools include the planting of