AGRICULTURAL BIOTECHNOLOGY: INSECT CONTROL BENEFITS

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1. Introduction

With the development of biotechnology methods, scientists now have the ability to transfer single genes from one living organism into another – regardless of species.

Corn, cotton and potato plants have been transformed successfully through genetic engineering so that certain varieties now contain a protein derived from a soil bacterium that kills certain insects when they feed on plants. The soil bacterium is known as *Bacillus thuringiensis* or Bt. The genetically transformed crops are referred to as "Bt corn", etc.

As the public debate regarding the role of biotechnology crops progresses over the next few years, it is imperative that a full discussion be made of the rationale for the use of these crops. Farmers use crop protection technologies because they provide cost-effective solutions to pest problems that, if left uncontrolled, would lower yields. In some cases, new effective technologies are used to control pests that are poorly controlled with existing technology. In these cases, yields go up as the new technology provides more effective control. In other cases, new technology is adopted because it is less expensive than current technology with equivalent control. There are cases in which new technology is not adopted because it is not competitive with existing technology.

U.S. farmers have planted a large portion of the nation's corn and cotton acreage with the Bt crops. A much smaller percent of the nation's potato acreage has been planted with the Bt potato variety . Table 1.1 shows estimates of the number of acres and percent of acreage of the U.S. potato, corn and cotton crops planted with Bt varieties. As can be seen, 16 million acres of corn, cotton and potatoes were planted with the varieties genetically modified to produce Bt proteins , inserted with biotechnology methods.

The purpose of this paper is to describe and quantify the insect control benefits provided on the Bt corn, Bt cotton and Bt potato acreage planted in 1997 and 1998. The pests that Bt crops control are described as are the alternative control methods. Estimates are made of yield changes and changes in insecticide use practices that have resulted thus far from the planting of the Bt crops.

TABLE 1.1
U.S. Crop Acreage Planted with Bt Crops (1998)

Crop	# of Acres (million)	% of Total Acreage
Field Corn	14.40	18
Cotton	2.30	17
Potatoes	.05	4

Sources: [114]

2. Corn

2.A. US Corn Production

Corn is the largest acreage crop grown in the US. Planted acreage totaled 80 million in 1998, which represents 25% of the acreage planted to all crops in the US [18] [116]. Average corn yield in 1997 and 1998 totaled 127 and 134 bushels per acre, respectively. Corn for grain production was estimated at 9 billion bushels in 1997 with a total value of production of $22 billion, which represents approximately 23% of the value of all crops grown in the US [19]. The major use of corn produced in the US is as a livestock and poultry feed (5.8 billion bushels) while food, seed and industrial uses (including sweeteners, fuel alcohols and starch) account for 1.8 billion bushels. Exports account for 1.6 billion bushels [18].

All 48 coterminous states have corn acreage and, in many states, corn is the single most important crop in terms of acreage and production value. Corn production is centered in the Midwest, where ten states account for 85% of the US acreage and production. Individually the states of Illinois and Iowa account for more than 10 million acres of corn each.

2.B. Insect Pests of Corn

Corn grown in the US is subject to attack by a number of insect pests in various degrees of severity. The more important pests include the northern and western corn rootworm, the black cutworm, the European corn borer and several species of wireworms.

There is some variation in the regional importance of insect and mite species damaging to corn. For example, in the southeast, billbugs are considered the number one insect problem for corn. In the Plains States, mites are an annual concern for corn growers because of arid conditions. Earworms generally are not considered as much a problem for field corn as they are for sweet corn production, for which absence of damage to the kernel is a prerequisite. Numerous foliage feeders of corn exhibit sporadic outbreaks (armyworms, aphids, leafhoppers). For the most part, the soil-inhabiting insects (rootworms, cutworms, wireworms) are considered the most important insect pests of corn. The second most important pest species of corn in most regions is considered to be the European corn borer [11].

Field corn growers spend approximately $380 million per year for insecticides and apply approximately 26 million pounds of insecticide active ingredient [29] [30].

Most insecticide applications in corn fields are made to the soil at planting for control of the soil-inhabiting insect species. If foliage feeders, such as armyworms, become a problem during the year, foliar applications are made – generally to a very small percent of U.S. corn acreage.

A recent survey in Iowa indicated the following targets of insecticide applications (% acres treated): corn rootworm (22%), black cutworm (6.1%), European corn borer (2.6%), other (0.6%) [13].

Bt corn is expected primarily to produce benefits resulting from control of the European corn borer. The Bt corn hybrids have no activity on aphids, spider mites, cutworms and soil insects such as rootworms, wireworms, grubs, seedcorn maggots and seedcorn beetles [31]. Although Bt corn also provides some control of earworms and stalk borers, those species do not pose a wide-spread threat to U.S. corn production. Bt corn controls Southwestern corn borer, a closely related species to the European corn borer. However, the Southwestern corn borer is generally a pest of corn in the Southeast and Southwest (such as Texas) corn-growing areas. Bt corn has had limited planting in these regions in the 1997-98 time period because of restrictions on planting the Bt corn crop in areas with plantings of similar Bt cotton varieties.

Several companies are developing biotech corn varieties that provide control of corn rootworms. These products are expected to enter the market in 2001 [79].

The discussion that follows of benefits of insect control through biotech corn hybrids is focused on the European Corn Borer.

2.C. The European Corn Borer

2.C.1. *Biology*

The European corn borer (ECB) is an introduced insect species. It probably arrived in North America during the early 1900s in corn imported from Hungary and Italy for the manufacture of brooms. First noticed near Boston, Massachusetts, in 1917, the European corn borer also was found later, in 1921, in areas bordering Lake Erie. It spread gradually from southern Michigan and northern Ohio. By the end of 1938, it had spread only as far west as the Wisconsin shore of Lake Michigan [26].

During its early history in the United States, the European corn borer produced one generation per year. By the late 1930's, a two-generation per year population appeared in the eastern and north central states. This two-generation per year European corn borer spread rapidly and soon became dominant in the central Corn Belt. It reached Illinois in 1939, Iowa in 1942, Nebraska in 1944, and South Dakota in 1946. Meanwhile, the single-generation European corn borer spread northward into northern Minnesota, North Dakota, and the Canadian provinces of Quebec, Manitoba, and Saskatchewan [26].

Later, three- and four-generation per year populations of European corn borer appeared in the south along the Atlantic Coast and southwestward in Missouri, Arkansas, Kansas, Oklahoma, and the Gulf states.

The insect has continued to spread throughout the corn growing areas of the United States. The European corn borer has spread northward into Canada, westward to the

Rocky Mountains, and southward to Florida and New Mexico. It is now present in all but the seven most western continental states.

As full grown larvae, European corn borers spend the winter in corn stalks, corn cobs, weed stems or in a spun-silk covering located in plant debris [3]. Winter survival is in the form of cold-hardy diapausing larvae that are capable of surviving a prolonged period of being frozen. The ECB begin spring development when temperatures reach 50° F. Adult moths leave emergence sites in plant debris and fly to nearby areas of dense vegetation, primarily grasses in conservation lanes, along waterways or near fence rows. These locations are referred to as action sites. Female moths must drink water before they begin emitting a sex attractant. When in the vicinity of a calling female, the responsive male performs a characteristic precopulatory dance, with vibrating wings extended upward, with genitalia extruded, and with claspers opening and closing. This performance is followed by mating. Multiple matings have been observed to occur relatively infrequently among females, but males are capable of mating daily during the 7-9 days of their adult lives [48]. The moths mate at night and the female leaves the action site to deposit eggs on the corn crop. After laying one or more egg masses, the females leave the corn crop and return to the action sites to feed, rest and wait for another suitable egg laying evening. Each mated female is capable of depositing an average of two egg masses per night for ten nights. Egg masses are small – approximately ¼ inch in diameter – and contain an average of 15 eggs.

Larvae emerging from the egg masses move directly into the whorl for shelter and food. The larvae feed on the leaves which result in small holes and patchy areas lacking leaf tissue. Eventually the larvae crawl out of the whorls and down the side of the stalk to burrow into the stalk of the corn plant, where they pupate during the summer. The boring larvae leave a characteristic frass when they tunnel into corn plants. Moths that emerge in mid-summer fly to dense vegetation, primarily foxtail grass to feed, rest and mate. The mated females deposit eggs on recently tasseled corn plants. Each second generation female can lay about 400 eggs during her life. The majority of the second generation larvae feed on sheath and collar tissue or pollen. Some of the emerging second generation larvae will feed on other protected areas, such as under the husk in the developing ear [3]. The larvae go into diapause and spend the winter in plant residue.

For field corn, yield losses from ECB larvae are primarily physiological losses from reduced plant growth. Stalk tunneling results in shorter plants with fewer and smaller leaves. Movement of water and nutrients can be restricted over the entire kernel-filling period. During whorl stage of corn growth, there is between 5 and 6% loss in grain yield for each larva per plant. During the corn development stage, the loss per larva per plant is about 2 to 4% [3].

In most cases the probability of a heavy attack by both generations is low. Since first generation moths prefer the most developed fields in an area and second generation moths generally target the least developed, many fields will escape significant damage by one generation or the other.

Three and five larvae per plant reduce corn yield by an average of 11.6 and 18.8% respectively [28]. After three borers per plant, the relationship between numbers of borers and yield loss starts to level out.

European corn borer-damage results in poor ear development, broken stalks, and dropped ears. Most yield loss can be attributed to the impaired ability of plants to produce normal amounts of grain due to the physiological effect of larvae feeding on leaf and conductive tissue. With persistent autumn winds and dry weather, tunneling in the stalks can increase stalk breakage, resulting in substantial loss of ears during harvest.

Tunneling affects corn yield primarily by reducing kernel weight. This probably occurs because the kernel growth weight is reduced by disruption of water and nutrient uptake and photosynthesis [28]. In some experiments, European corn borer feeding reduced the number of kernels per ear [28].

Experiments conducted between 1991 and 1994 on farmers' fields in Iowa showed that second generation borers by themselves caused yield losses of at least 33 bushels (1991), 9 bushels (1992), 14 bushels (1993) and 10 bushels (1994). These losses were mostly from stalk tunneling.

Establishment is accomplished largely by sheer force of numbers, for fewer than 25% of the larvae survive their first 48 hours, and far fewer than 5% attain maturity. Newly hatched larvae can be blown off the leaves by winds, crushed by moving plant parts, knocked down by heavy rainfall or dehydrated from hot weather before they find a place to hide in the whorl [48]. Larvae also can be killed by several predators, parasites and diseases, such as *Beauvaria*, that causes a white fungal growth on the dead larvae.

Research has shown that storms with violent winds greatly reduce adult ECB populations and these storms could account for much of the local variation in ECB populations [23].

A population survey of European corn borers was conducted in Boone County, Iowa, during the period 1951-1970. It was estimated that first generation egg density averaged 44,000 per acre while second generation egg density was 175,000 eggs per acre [17]. The number of larvae per acre averaged 3,500 in the first generation and 17,000 per acre in the second generation.

Borer survival is estimated to be three borers per egg mass on average. Research has shown that an overall survival rate of 1.3% is sufficient to sustain economic levels of infestation [55]. Corn plants heavily infested by first generation borers are unattractive to egg-laying moths of the second generation. Infested corn plants produce an odor that is repellent to the moths. In addition, the excrement and frass of the first generation larvae repel the second generation moths [55].

Feeding by corn borers also gives disease organisms entry points into plants and grain, increasing disease incidence. Stalk rot incidence is associated closely with corn borer feeding. Caused by soil-borne fungi, this disease reduces yields by reducing translocation within stalks and increases harvest losses by leading to stalk breakage and ear drop. Yield losses average four to five percent per rotted internode [3]. In some cases larvae from just one corn borer egg mass per plant can lead to four rotted internodes per plant, or a yield reduction of 16 to 20 % caused by stalk rot in addition to yield losses due to the insect itself. Feeding on kernels increases the incidence of mycotoxin-producing fungi.

2.C.2. *Varietal Resistance*

Corn produces both male and female gametes on the same plant. The sperms are produced in pollen in the tassel at the top of the plant, and the eggs on the ear shoots that develop at the nodes of the stalk, usually about midway between the base of the plant and the tassel [77]. A single tassel may produce 25 million pollen grains. A microscopic pollen grain lands on the tender, sticky silk emerging from the young ear shoot. Under favorable circumstances, a pollen tube emerges within a few minutes from this pollen grain and grows down through the corn silk until it reaches the female cell on the soft cob [77]. The male cells unite with the female cells at its base, and the development of a kernel of corn is begun immediately.

Thus, every silk represents the possibility of one kernel of corn. Since there are about 800 to 1,000 silks emerging from the ear shoot of an ordinary field corn plant, there are approximately 800 to 1,000 kernels of corn on the average ear when it is harvested in the fall. If for any reason pollen does not come into contact with the ear silks, no kernels will be formed, and nothing but a big fluffy cob will be found in the husk at harvest time [77].

In order to produce hybrid seed that combines the traits from two different corn varieties, breeders usually plant four to five rows of one variety, that will be the seed parent, alternated with one row of the variety selected to be the male parent. The tassels are removed from the seed parent so that the only source of pollen in the field is in the plants in those rows planted to the male parent. In this way a cross is forced upon the plants in the rows used to produce seed [77].

Selection for resistance in corn to the European corn borer has been an important part of breeding programs for the past six decades. In the beginning, inbred lines with substantial resistance to larval survival were found in small numbers. Research indicated that resistance to first generation ECB has a chemical basis. The larval feeding results in injury to the plant tissue, which causes an enzymatic conversion of a glucoside to the chemical, 2,4-dihydroxy-7-methoxybenzoxazin-3-one (DIMBOA). DIMBOA appears to function as a repellent and/or feeding deterrent [1]. Research found a significant correlation between the concentration of DIMBOA in the leaf-whorl tissue and resistance to the first generation borers [2]. Selection based on DIMBOA content produced inbred lines that are highly resistant to leaf feeding by first generation corn borers [2]. One limitation of the increased resistance is that DIMBOA does not protect against damage due to sheath feeding by the second generation borer. The level of DIMBOA declines as the plant matures. Sheath and collar tissue have been found to contain very low, ineffective concentrations of DIMBOA [48]. Germplasm resistant to second or third generation European corn borer sheath and collar feeding has been difficult to find [3].

In 1969 approximately 21 million acres of corn were planted to hybrids whose pedigrees contained at least one inbred line with an intermediate resistance to first generation corn borer [3]. Since the mid 1970's, however, the acreage planted to hybrids resistant to leaf feeding has decreased dramatically [3]. This is because inbred line B73, which is high yielding, but susceptible to leaf feeding, is used widely in hybrid combinations [3]. Research demonstrated that the yield potential of the susceptible hybrids based on B73 was great enough to compensate for the greater loss to the European corn borer [5]. Even with heavy corn borer damage, the yield of the susceptible cultivars was comparable to the resistant ones. In years when corn borer populations are low or moderate, the susceptible cultivars are likely to outyield the resistant ones [5].

In many corn hybrids, DIMBOA levels are high in very small plants. If the first generation ECB hatch occurs when the corn plants are very small, most of the larvae fail to become established. They are repelled and wander off and die [3].

2.C.3. *Biological Control Research*

Although the ECB was the focus of the most extensive biological control program ever carried out by USDA, the program was not an overwhelming success [8] [7].

It was early realized that one of the factors contributing to the phenomenal increase of the European corn borer in the U.S. was the lack of its natural predators [6]. In 1919, the USDA established the European Parasite Laboratory (EPL) in France for the purpose of collecting natural enemies of the corn borer in Europe [7]. At its zenith in 1931, there were 430 temporary field workers hired to collect ECB larvae throughout France and Italy [7]. Importations from Europe during the years 1920-38 totaled approximately 2.7 million adult parasites [8]. Of the 24 species of parasites that were imported and colonized, six became established. A fly, *Lydella thompsoni*, was by far the most effective of the introduced species.

Adult females of *L. thompsoni* lay an egg either directly into the host tunnel at the opening or in the frass and excrement that cover an opening [9]. The females apparently are attracted to a corn borer tunnel by the odor given off from the excrement and possibly from the host itself. The female runs hurriedly along the stalk and appears to be searching from side to side. Often when it comes upon frass, it feeds a moment before inserting an egg. The parasite larvae penetrate the host larvae and become an internal parasite of the corn borer [9].

During the years 1948-50, surveys in 25 states showed that *L. thompsoni* was parasitizing 10-50% of the hibernating borers. Sometime between 1955 and 1961 *L. thompsoni* appears to have disappeared from the Corn Belt [8].

L. thompsoni has been reintroduced into the US and in some places appears to be having an impact on the corn borer populations [27]. However rates of parasitism have not reached previous levels.

One cause of the disappearance of the introduced predators are pathogens and parasitic wasps which attack them and reduce their numbers [22].

General predators of ECB include lady beetles, minute pirate bugs, predacious mites and birds that feed on the eggs and larvae.

Although insect predators play an important part in corn borer reductions at some locations in some years, they cannot be depended upon year after year, or in any given year, to alter significantly the borer populations at any specific location because of their sensitivity to environmental conditions [59].

2.C.4. *Insecticide Trials*

A large number of tests have been undertaken since the 1920's to determine the efficacy of insecticides for control of the European corn borer. The early tests were with arsenic, nicotine, ryania and rotenone. Research demonstrated that four applications of these materials could reduce corn borer populations by 92% [6]. Research with DDT began in the 1940s and indicated that with the proper timing of a four-treatment schedule, better than 90% corn borer control could be achieved [6].

Corn borer control was improved and simplified by the development of granular formulations of insecticides and machines to apply them [6]. The corn plant and the feeding habits of the borer are particularly adapted to this type of control. The leaves of the corn plant form a natural trough that directs the granules deep into the whorl or on the leaf axils where the newly hatched borers feed [6]. Experiments in the 1950's and early 1960's were concerned primarily with granular organophosphates and carbamates including carbaryl, carbofuran, monocrotophos, parathion, EPN and ethoprop. All of these tested insecticides provided control equal to that of DDT [15].

The first tests in the 1960's for control of European Corn Borer with systemic insecticides indicated no control with these chemicals [41]. Systemic insecticides are applied to the soil and are taken up in the growing plant. Insects receive a chemical dose when they feed on the plant. Experiments with carbofuran in the 1970's indicated that it did provide some systemic control of the ECB when applied to the soil at planting [41].

Recent experiments with the systemic insecticide fipronil indicates that it provides a high level of control of first generation corn borers (76%) [67]. Applied to the soil, fipronil is taken up in the plant tissue, where it remains active for up to 10 weeks.

Granular formulations are recommended for first generation control because they stay in the whorl leaves where small corn borer larvae are feeding. Liquid formulations stick to leaves and move out of the whorl region as the plant grows.

There are five active ingredients recommended for control of European corn borer in Illinois: chlorpyrifos, lambdacyhalothrin, methyl parathion, permethrin and Bt microbial insecticides [14].

Once the larvae bore into corn stalks, they are protected from insecticide applications. Timing of insecticide applications is critical because sprays are effective only during the two- or three-day period after the eggs hatch and before the larvae bore into the stalks. However, egg laying can occur over a three-week period. Most insecticides are effective for only a 7–10-day period. If application is delayed too long, larvae from the first hatching eggs will have bored into the stalks. If applied too early, the insecticides will have degraded before all the larvae have hatched.

Careful timing of insecticide sprays for second generation corn borers can produce very high levels of control. For example, Illinois experiments in 1997 demonstrated that lambdacyhalothrin reduced the number of cavities per plant from second generation ECB by 96% [76].

Research in Iowa corn fields demonstrated that the use of insecticides for control of both first and second generation ECB produced from 11 to 17 more bushels per acre than the untreated portion of the fields [78].

Table 2.1 shows the increased yields from five different corn fields in Iowa that received one insecticide application for second generation European Corn Borer. As can be seen, the increased yield resulting from insecticide treatments ranged from 7 to 33 bushels per acre [3]. These fields were chosen without any indication of the potential for corn borer population.

University recommendations for ECB control are based on one carefully timed insecticide application for first generation and one carefully timed application for second generation control. Growers are advised to expect 80% control of first generation larvae and 67% control of second generation [14]. The cost of a single insecticide application (including the cost of aerial application) is estimated at $14 per acre [14].

2.C.5. *Monitoring*

Because of the window between egg hatch and entry into stalks, the most critical aspect of chemical control for ECB is to determine proper application timing. Numerous entomologists have attempted to find foolproof methods of determining the proper time to achieve the degree of control acceptable with a minimum number of applications.

Treatment guidelines for first generation corn borers are based on active whorl feeding and live larvae. Visual samples of percent damage should be taken from 5 representative sets of 20 plants for every 40–50 acres. Assessments of actual larval density and size can be assessed by grabbing the upper 5–7 leaves of the corn plant and pulling straight up to detach the whorl from the basal part of the plant. Two or three plants should be destructively sampled per 50 acres. Leaves should be unwrapped carefully and examined for fresh larval feeding and live larvae. The number of live larvae in each plant must be recorded. Since additional hatching can occur, the fields should be rescouted every 3 to 5 days until insecticide is applied or scouting shows the population is not large enough to justify treatment.

Second generation scouting is completely different from first generation scouting; it focuses on finding egg masses instead of larvae. To determine egg mass density, 20 consecutive plants in a row should be examined at 5 representative locations within the field. The underside of leaves should be scouted. Sampling should be avoided within 100 feet of the edge of the field. Egg mass sampling is necessary every 2 to 3 days.

In 1985, extension entomologists at Iowa State University developed a worksheet that uses a six-step mathematical formula that calculates the costs versus the benefits of chemical control. The worksheet estimates the potential yield loss from a known ECB population, determines the yield loss that could be prevented with an insecticide and then compares the preventable loss based on the market price for corn against the cost of control.

A survey of Iowa and Minnesota corn growers revealed that while 66% of growers perceived ECB to be a serious pest, only 35% had ever scouted their fields even once [43]. Scouting for insect populations is more common in the Western Corn Belt where irrigation is prevalent and corn yield potential is higher. Scouting for ECB and other pests by professional crop consultants is more prevalent in Nebraska than in any other state. In 1994, Nebraska farmers employed professional scouts to scout 24% of their corn acreage [39]. The 10 State Corn Belt average was only 6.7%.

Cost of scouting field corn for insects currently averages from $3 to $7 per acre for the season [3].

2.C.6. *Insecticide Use*

Several pesticide use surveys provide estimates of the extent of corn acreage treated with insecticides for European corn borer control (1985–1995). A USDA survey of corn extension entomologists in 1985 resulted in an estimate that 4% of the Corn Belt's acreage was treated with insecticides (primarily carbofuran) for European corn borer control [11]. A 1990 survey of Illinois corn growers estimated that 4.5% of the state's corn acreage was treated for first generation corn borers while 0.2% of the acreage was treated for second generation corn borers [12]. The primary insecticides identified for corn borer control were carbofuran, chlorpyrifos, fonofos and permethrin. A 1995 survey in Iowa indicated that 2.6% of the state's corn acreage was treated for European corn borer [13].

In a recent survey, Extension Service entomologists were asked for estimates of the percentage of corn insecticides used in 1996 that was for control of the ECB [40]. The survey indicated that ECB control is the most common usage in corn for permethrin and methyl parathion (60–70% of use) while lambdacyhalothrin is used about equally for ECB and other corn pests, and chlorpyrifos is more commonly used for other corn pests (15% usage for ECB). By multiplying these share estimates times USDA grower survey estimates of corn acreage treated with these insecticides, estimates were made of the percent of corn acreage treated for ECB: chlorpyrifos (1.2%), lambdacyhalothrin (1.0%), methyl parathion (1.2%) and permethrin (2.8%). By multiplying the share estimates times the national usage of these active ingredients (in terms of pounds applied), it was estimated that 1.474 million pounds of active ingredient were used to control the ECB in

1996: chlorpyrifos (882,000), lambdacyhalothrin (13,000), methyl parathion (352,000), and permethrin (227,000).

One exception for spraying during the corn growing season is on the High Plains irrigated production area of Nebraska, Kansas, Colorado and Texas. In these areas, control of spider mites in corn is an annual problem. Because of the prevalence of continuous corn planted acreage in the High Plains, some growers opt for an in-season insecticide application for adult rootworms. Corn fields are scouted more frequently in the Plains States than elsewhere. This scouting also detects presence of the European corn borer (ECB). As a result, treatment for the ECB is much higher in the Plains States than in the Corn Belt. For example, it has been estimated that an average of 20% of the scout-contracted corn fields in Nebraska are treated annually for first generation corn borer and 40% of the scout-contracted corn fields are treated for second generation borers [52]. These in-season ECB applications often are timed as part of the treatment for mites and adult rootworm, since the main mite insecticide (bifenthrin) and the main adult rootworm insecticide (methyl parathion) also control the ECB.

In a 1990 survey, corn farmers in Kansas reported that they used bifenthrin on 6% of the state's acreage for European corn borer control while carbofuran was used on 6% of the state's acreage for control of the Southwestern corn borer [54].

A recent report to EPA summarized market research data concerning the extent of insecticide use in U.S. field corn for corn borer control (% total U.S. acres treated): 1993 (3.0%), 1994 (3.9%), 1995 (4.9%), 1996 (6.3%) and 1997 (7.1%) [44]. The report estimated that the percent of corn acreage treated for corn borer by region in 1997 was 25% in the Southwest region and 6% in the Southeast.

A survey of ECB damage in Iowa corn fields in the early 1980's revealed that every scouted field had some plants damaged, and county means for percentage damaged plants ranged from 7 to 23%. It was estimated that 8% of the scouted fields exceeded the economic threshold for first generation ECB [21].

An analysis of 30 years (1955–1984) of ECB infestation data in Illinois indicated that 10% of the fields were infested with three or more borers per stalk [20]. This infestation level was estimated to translate into a 9 to 15% yield loss due to the second generation of ECB [20].

In eastern states, such as Pennsylvania, corn fields are small in comparison to those in Corn Belt states, and fields often are located on sloping ground [90]. Small size and the topographic characteristics of fields often make aerial applications impractical and ground applications dangerous.

More farmers ignore the ECB than treat it with insecticides. This may be the result of the difficulty of scouting, calculating the economic threshold and determining the proper timing of an insecticide application plus the costs of management [34].

Historically the reluctance stems from several factors:

- larval damage is hidden
- scouting multiple times each season takes time and requires skill
- competing demands for their time and resources from activities such as weed control and harvesting of alfalfa
- a desire to cap total input costs for corn cultivation, especially if the perceived benefits from the additional expenditures are considered to be small

Most insecticides for control of ECB are applied aerially although high clearance equipment, when available, also can be used [3].

2.C.7. *Corn Losses to ECB*

The USDA issued annual reports for 1942–1974, in which estimates were made of the yearly corn production losses from European corn borer damage [35]. The annual losses varied from a low of 33 million bushels (1952) to over 300 million bushels per year (1949, 1971). (See Figure 2.1.) USDA calculated that the average annual loss (1942–1951) of 58 million bushels of corn represented an equivalent loss of 1.8 million acres of corn production [37].

Figures 2.2, 2.3 and 2.4 chart ECB densities (larvae/stalk) for Illinois, Wisconsin and Minnesota for 1943–1998 (IL) and 1963–1998 (WI/MN).

More recent estimates of aggregate corn production losses include the years of 1983 and 1995 in Minnesota. For 1983, it was estimated that Minnesota corn growers lost $107 million in corn production because of corn borer damage while in 1995, it was estimated that damage from the European corn borer resulted in $285 million in lost corn production in Minnesota [38] [31].

In a 1992 survey in Michigan, 80% of corn growers reported suffering yield losses exceeding five bushels per acre in their fields in the previous ten years [56]. In a survey of Extension Service entomologists in the Corn Belt, most respondents (71%) indicated that corn yield loss exceeding five bushels an acre occurred on over 10% of the fields in their states [56].

A summary of economic losses in Nebraska for the years from 1971 to 1980 indicated that losses associated with the ECB were $72 million annually [24].

In a recent survey of Iowa farmers, 57% reported an average loss of 5.4 bushels per acre from ECB whereas the remainder (43%) reported no loss to the ECB [34].

Recently it has been estimated that annual losses of corn to uncontrolled ECB exceed $1 billion every year [3]. This estimate is based on the 1983 loss estimate from Minnesota of $107 million (cited above) and an assumption that Minnesota represents 10% of the national corn total (based on acreage)[53].

2.C.8. *Alternatives Research*

Research is underway with a fungus, *Beauvaria bassiana*, that makes corn borers sick [45]. Research has demonstrated that spraying suspensions of *B. bassiana* spores into the corn whorl before tunneling reduced corn borer tunneling in stalks about one-third [45]. Two other enemies of corn borers, the fungus-like microsporidium, *Nosema pyrausta*, and a tiny wasp called *Macrocentrus grandii* are being researched [45]. There is concern, however, that the two beneficial organisms may work against each other.

Research in 1997 at the University of Illinois indicated that none of the *Beauvaria bassiana* treatments produced significantly different ECB control results from the control plots treated with blank granules [75]. Research in 1998 at the University of Illinois has indicated that some *Beauvaria bassiana* treatments seem to offer some protection against attack by first and second generation ECB [74].

Researchers have also examined the possibility of shredding stalks and leaving shorter stubble as a means to lower overwintering borers. For example, mowing stalks in no till fields resulted in up to 80 % mortality [46]. To be successful, mowing would have to be implemented over a wide area.

USDA research has involved treating the grassy areas around cornfields with the insecticide carbaryl, that kills most of the female borers before they can return to the cornfield to lay their eggs [47]. Four treatments are needed to control the spring and summer moths.

Current research attention is focused on a group of tiny parasitic wasps called *trichogramma*. Experimentally, the *trichogramma* wasps are released at a rate of 200,000 or more per acre [3]. These wasps attack the eggs of the European corn borer. However, the trick is to ensure that they are present in the proper place at the proper time in high enough numbers to destroy the ECB eggs before they can hatch into the damaging larval stage [27]. Ways must be found to reduce the cost of the parasites before augmentative releases of *trichogramma* will become economically feasible in field corn [27].

The quality of released wasps is still too inconsistent for reliable use in U.S. corn fields [3].

With grant support from the Leopold Center, Iowa State University entomologists are investigating the use of pheromone mating disruption for ECB [82]. Use of this system has resulted in a reduction of mating of 30-40% by free flying wild corn borer females.

2.D. *Bacillus thuringiensis*

Bacillus thuringiensis (Bt) is a naturally occurring soil bacterium that produces crystal proteins that selectively kill specific groups of insects [31]. Bt was first isolated in 1901 in Japan from diseased silkworm larvae. There are several strains of Bt, each with differing crystal proteins (Cry proteins). More than 60 Cry proteins have been identified. For example, Cry proteins identified from Bt *kurstaki* include CryIA(a), CryIA(c), CryIIA, and CryIIB. Research in the 1960's identified Bt Cry proteins with insecticidal activity against the European corn borer.

The subspecies Bt *kurstaki* controls Lepidoptera larvae, including ECB. Bt *israelensis* controls mosquitoes and flies, and Bt *tenebrionis* works against Colorado potato beetle and elm leaf beetle.

Bt endotoxins must be ingested by larvae to cause death. The uniquely high pH of Lepidoptera larvae guts solubilizes the toxin crystals and releases a molecule that is not toxic until enzymes found in the gut cause the release of active toxin. This toxin causes paralysis of the insect's gut and mouthparts within minutes. The toxin binds to the cells lining the midgut membrane and creates pores in the membrane, upsetting the gut's ion balance [65].

The insect gut wall breaks down within 24 hours. Bacterial spores germinate and invade the body cavity of the insect. The insect dies from toxins attacking the gut wall, by general body infection, and food deprivation [33].

One of Bt's most desirable characteristics is its selectivity; only certain insects are susceptible to the delta-endotoxin. Each endotoxin is effective against specific insects. Each variety of Bt can produce one or more of these toxins. Alkaline (basic; pH greater than 7) solutions activate the delta-endotoxin, and different varieties may require different pHs. Certain enzymes must also be present in the insect's gut to break the crystal into its toxic elements. In addition, certain cell characteristics in the insect gut encourage binding of the endotoxin and subsequent pore formation. The age of the insect is also a factor, the younger larvae being more susceptible than older larvae [65].

The development of a fermentation process for the bacterium enabled the production of formulated insecticide products.

Research demonstrated that granular formulations of Bt gave effective control of first generation European corn borers [42]. However, the bacteria did not give satisfactory control of second generation European corn borers. Although granular formulations of Bt often gave control comparable to that obtained with carbofuran granules, ECB control with Bt was more variable [43].

One drawback to conventional foliar applications of Bt has been that it is short-lived when sprayed on plants because the toxic portion is susceptible to breakdown by ultraviolet radiation, rainfall, heat and desiccation [32].

Research in 1929 indicated that Bt applied as an aqueous suspension reduced the populations of manually infested plants from 50 borers per plant to 1.3 borers per plant [57]. Extensive laboratory studies with Bt carried out in the 1950's demonstrated that mortality increased as the spore count increased [58]. Field tests, however, were inconclusive, and the researchers concluded that Bt did not constitute a practical means of ECB control [58].

Experiments with Bt produced variable laboratory and field results in terms of ECB control [60]. Some of the effects of reduced efficacy of Bt because of ultraviolet radiation and low temperatures were decreased by encapsulation of the microbial insecticide [61].

The activity of the toxin in an insect depends on gut pH, the presence of specific enzymes, reducing agents and binding sites in cell membranes.

2.E. Bt Corn

Beginning in 1996, several seed companies commercially introduced new corn hybrids that have been altered genetically to produce a protein toxic to corn borers. These hybrids contain a gene from the bacterium *Bacillus thuringiensis* (Bt), that has been added to the genes in the corn plant to produce a protein not previously present in corn [32].

The ECB ingests the Bt protein in trying to feed on the plant. The toxin binds to the gut membranes, and pores are formed. Cells in the gut rupture and the ECB larvae die.

Corn plants were transformed through a variety of methods, including the use of a gene gun that shoots tiny particles carrying genetic material into cells. In the development of Bt corn, the genetic material that was inserted includes the gene for a specific Cry protein, a promoter that controls where and how much of the protein the plant will produce and a genetic marker that allows for the identification of successful transformations. Successful transformations, called events, vary in what genetic information is transferred and where it is inserted into the corn's DNA.

The USEPA must register events before they can be used in commercial seed production. To date, EPA has registered five unique Bt events for corn: 176 (Novartis Seeds and Mycogen Seeds), BT11 (Northrup King/Novartis Seeds), Mon 810 (Monsanto), DBT418 (Dekalb Genetics), and CBH 351 (AgrEvo). The Mon 810 and BT11 events are used in production of YieldGard® corn. Event 176 is sold as KnockOut® by Novartis and Nature Gard® by Mycogen. The DBT418 event is sold as BT-Xtra®. The CBH351 event is sold as Starlink® by AgrEvo. These events vary in how much Cry protein is produced in the plant and where it is produced, thus affecting ECB control. The Starlink® corn hybrid contains the Cry9C protein while all the other BT hybrids contain the Cry1A(b) or Cry1A(c) protein. The Cry9C protein binds to a different site in the insect's gut. Cry9C is also toxic to black cutworms [50].

An initial 1992 field test evaluated whether plants containing the Bt gene suffered less damage when challenged with extremely high artificial ECB infestations [91]. The major conclusion of the study was that a very high level of protection from ECB damage was maintained in Bt corn during repeated heavy infestations of this pest.

Bt hybrids were infested with 300 larvae/week for a total of 8 weeks. The first four infestations corresponded with the first-generation ECB infestation period; whereas, the latter four infestations corresponded with the second-generation period. These levels of infestation were approximately 12 to 96 times the economic threshold for second-generation ECB infestation. The leaf-feeding damage typical of first-generation ECB was visually evaluated. Second-generation ECB damage was assessed by measuring tunnel lengths in the stalk [91].

Almost all Bt plants showed no more than slight “window pane” first-generation ECB damage to the epidermal layer of leaf tissue. Control plants typically had elongated lesions and broken midribs. As the season progressed, control plants senesced and disintegrated, but Bt plants remained green. At the end of the season, most Bt plants had 0-5 cm tunneling damage; whereas, the mean tunnel length in control plants ranged from 28 to 113 cm. These results provided the first field demonstrations of the high level of ECB control provided by the Bt gene. Relative to the control plants, Bt plants controlled approximately 95% of ECB damage, as measured by tunnel length [91].

The Starlink® and YieldGard® corn hybrids express the Bt protein in all plant cells throughout the season providing 98% control of first and second generation ECB [62]. In the other Bt corn hybrids, the Bt protein is only expressed in the plant’s green tissues and pollen, and not expressed significantly in roots, pith, kernels or silk. Because some second generation larvae initially colonize ears to feed on silks and developing kernels, these larvae may survive on Bt corn hybrids in which the Bt is not expressed in all plant tissue. These hybrids provide 98% control of first generation ECB but only 50-75% of second generation larvae [62].

ECB feed on Bt corn only enough to make a tiny scar (not even a hole) in the corn leaf or sheath. Most European corn borer larvae on Bt corn die within their first day after attempting to feed [3].

In 1997, the University of Minnesota compared Bt and non-Bt hybrids at three southern Minnesota locations. Bt hybrids containing the YieldGard® gene averaged 15, 11.4 and 11.8 bushels per acre more than their non-Bt counterparts [84]. At three northern Minnesota sites, all Bt hybrids averaged 23.8 bushels per acre higher than non-Bt hybrids, with YieldGard® hybrids outyielding other Bt hybrids. In University of Nebraska tests in

1997, Bt hybrids consistently yielded more than their non-Bt counterparts. At one location, the yield advantage for Bt hybrids ranged from 19 to 44 bushels per acre [85]. The yield advantage for Bt corn hybrids is attributed to ECB control.

Recent research (1998) at the University of Illinois continues to demonstrate that all Bt hybrids had significantly fewer cavities per plant and percents of plants with cavities than the non-Bt hybrids not treated with insecticides and the non-Bt hybrids treated with insecticides [66].

In a University of Minnesota study, ECB tunnels per 10 plants were recorded for a non-BT hybrid (21.2/10 plants), an Event 176 hybrid (2.7/10 plants) and a YieldGard® hybrid (0.1 tunnel/10 plants) [31].

Growers are advised not to expect 100% control of ECB with Bt corn hybrids, even those with full season expression in all plant tissues. There will be a small number of plants in which the Bt toxin is not expressed. The expectation is that 96% average control is realistic [31].

2.F. Aggregate Effects of Bt Corn Adoption

In 1997, U.S. farmers planted Bt corn seed on 5% of the nation's acreage (4 million acres) while in 1998 18% of the nation's acreage was planted to Bt corn (14.4 million acres) [25] [114].

The year 1997 was typical for European corn borer infestations while 1998 was an extremely light infestation year. See Figures 2.2, 2.3 and 2.4.

The rainy June of 1998 was a major contributor to poor survival of first generation ECB larvae. Additionally, populations may have been reduced because of increased planting of Bt corn [69].

A survey of Bt corn acres in 1997 in six states (Illinois, Iowa, Kansas, Minnesota, Nebraska and Pennsylvania), indicated that approximately 75% of the growers planted YieldGard® as the primary Bt brand [70]. Bt corn users indicated that previously they had applied insecticides to control ECB populations one out of every two years. Thirty percent of the Bt corn users indicated that they planted Bt corn in 1997 in order to eliminate insecticides for corn borer control.

The USDA has surveyed corn growers regarding insecticide use on an annual basis in the 1990's [10]. However, target pests are not identified in the USDA surveys. Figure 2.5 charts USDA survey data 1994–1998 for the five insecticides that currently are recommended for control of European Corn Borer: chlorpyrifos, permethrin, lambdacyhalothrin, methyl parathion and Bt.

As noted above, with the exception of Bt (foliar) these insecticides are used typically for several target pests, including cutworms, rootworms, armyworms and European corn borer. The USDA data show an increase in the use of these five insecticides between 1996 and 1997, a finding consistent with market research data. (See above) and the greater incidence of corn borers in 1997. Of interest is the decline in use of four of the insecticides comparing 1995 with 1998: chlorpyrifos (-1%), permethrin (-3%), Bt (-1%), and methyl parathion (-2%). Several explanations are possible to explain the change from 1995 to 1998: the introduction of lambdacyhalothrin that was used on 2% of the acreage in 1998; less usage for target pests other than ECB; and/or less usage for ECB control due to the introduction of Bt corn or due to lighter than normal ECB pressure in 1998. The aggregate reduction of the percent acreage treated with the five insecticides is 7%. Assuming that 2% of the change is attributed to the introduction of lambdacyhalothrin, implies that a 5% decline occurred as a result of changes in the target pest complex, including ECB and other pests.

For analytical purposes, it is assumed that one-half of the decline in the usage of the four insecticides (2.5%) was due to the introduction of BT corn, implying 2 million fewer acres sprayed for ECB. As noted above, approximately 5% of the nation's corn acres were sprayed for ECB control in 1995. A reduction in ECB sprays of 2.5% because of the introduction of BT corn implies that 2.5% of the nation's corn acreage was sprayed for corn borers in 1998.

A comparison by Monsanto of yield data from 310 locations across the Corn Belt in 1997 indicated that Bt corn outperformed non-Bt hybrids by an average of 10.8 bushels per acre [73]. Individual states where the plots yielded more than a 10 bushel per acre advantage for the Bt corn include Nebraska, Kansas, Iowa, South Dakota and Illinois. The yield advantage for Bt corn in 1998 was lower than 1997 because of the lighter infestations of ECB. Most states averaged four bushels or less in terms of yield advantage [72]. The average yield advantage for Bt corn from all locations in 1998 was 2.4 bushels per acre.

There was considerable variation between 1997 and 1998 in the Bt corn yield advantage for individual states and between states in those years. Monsanto data indicate the following yield advantage for Bt corn by state and year (bushels/A): Illinois (1997, +17.4; 1998, +1.5), South Dakota (1997, +12.9; 1998, +7.7), Iowa (1997, +12.2; 1998, +3.1), Kansas (1997, +12.0, 1998, +3.7), and Nebraska (1997, +10.5; 1998, +4.2) [72].

Novartis Seeds has reported on corn yield comparisons of Bt hybrids *vs.* non-Bt near isolines as follows: 1997 (+9.4 bushels per acre), and 1998 (+4.6 bushels per acre) [86]. These averages were computed from 1048 and 580 paired comparisons for 1997 and 1998, respectively.

In 1997, Iowa State University entomologists planted 16 BT hybrids at 14 locations around the state. When yield data from all sites was averaged, the BT hybrids had a 9.6 bushels per acre advantage [68].

An evaluation of corn yield in Iowa in 1998 demonstrated that the yield of Bt corn hybrids was 2.9 bushels per acre higher than non-Bt hybrids, in general [51]. In 51 out of 84 comparisons (61%), the Bt hybrids outperformed their non-Bt counterparts. The data showed that, even without significant corn borer pressure, Bt hybrids are capable of yielding as well as, if not better than, their non-Bt counterparts [51].

Pioneer data from on farm side-by-side yield comparison showed a Bt corn yield advantage of 17 bushels/acre (35000 comparisons) in 1997 and of 7 bushels/acre in 1998 (64713 comparisons) [118].

Averaging the four values that compared Bt corn yields with non-Bt yields indicates a 11.7 bushels/acre and a 4.2 bushels/acre advantage for 1997 and 1998 respectively.

Assuming that the average yield increase on Bt corn acres was 11.7 bushels in 1997 (4 million acres) and 4.2 bushels in 1998 (14.4 million acres) implies an aggregate increase in corn production of 47 million bushels in 1997 and 60 million bushels in 1998. Assuming an average yield of 130 bushels of corn per acre (1997/98 average), it is estimated that the annual equivalent of 350,000-450,000 acres of corn would have been lost to ECB damage in the absence of Bt corn in 1997-1998.

The price premium for using Bt corn was approximately $10 per acre in 1997 and 1998. Assuming that a bushel of corn generated $2.43 in income in 1997 and $1.95 in 1998 [87] implies that the average income change per Bt corn acre in 1997 was +$18 while in 1998 the average per acre income change was –$1.81. In the aggregate, corn farmers gained $72 million in income in 1997 while they lost $26 million in income in 1998 from the planting of Bt corn. Bt corn delivered $112 million in benefits in 1997, and $118 million in benefits in 1998. These are average values across the nation’s corn acreage. Some corn farmers faced heavy ECB infestation in 1998 and derived a positive net return from its use. Likewise, some growers faced no borer activity in 1998 and derived no additional return from Bt corn.

As can be seen in Figures 2.2, 2.3 and 2.4, 1998 was an extremely light year for European corn borer infestations in the Corn Belt. In order to gain a perspective on the annual value of Bt corn, Monsanto conducted an analysis using the average annual infestation values for ECB in Illinois 1986-1998. (See Figure 2.2.) The calculation assumes that .25 larva per stalk is first generation with an associated yield loss of 5% per larva. The remaining number of ECB larvae per stalk were estimated to be second generation with an estimated yield reduction of 3% per larva. Using this methodology, the percent yield loss per acre was calculated for each year. These estimates were multiplied by the annual average value of a bushel of corn and the average yield of corn per acre to determine the income loss per acre from uncontrolled ECB. It is assumed that if Bt corn had been planted, the yield loss would have been reduced by 96% at a cost of $8 per acre (the price premium for Bt corn in 1999). For 1997 and 1998, the Monsanto calculation relies on the actual bushel per acre advantage recorded for Bt corn in Illinois. (See above.) By subtracting the price premium of the Bt corn from the value of the predicted yield increase in Illinois, estimates were made of the average annual per acre value of Bt corn in Illinois for each year 1986-1996. These values are shown in Figure 2.6.

As can be seen, in 10 of the 13 years 1986-1998, corn growers would have achieved a net positive return of $4 per acre to $37 per acre. In three years (including 1998), the net return would have been a loss because of extremely low borer populations in those years.

A similar analysis using historical ECB damage data for Minnesota 1988-1995 gave similar results. The projected benefits averaged $17.24 per acre, significantly exceeding the assumed selling price of $7-10 per acre [31]. However, in low infestation years (5 years), the yield protection provided by Bt corn barely covered the cost of the seed while during high infestation years (3 years), the values of the yield increases ($28-$50 per acre) were four to five times the added seed cost.

University Extension entomologists are urging corn growers to view planting BT corn as insurance against the possibility that ECB infestation levels will be as they are typically seven out of ten years. [64] It is not possible to predict the ECB levels based on incidence in the previous year.

One consequence of the large acreage planted to Bt corn is that farmers have seen the impact on their fields of controlling the ECB: "If there's one thing many growers have learned from trying Bt hybrids, it's that they never realized how much damage European Corn Borer has been doing to their yields" [80].

The USDA recently reported on yield differences between Bt corn acreage and non-Bt corn acreage for 1997 and 1998 {117}. The USDA analysis shows a reduced corn yield for 1997 in one region and a significant increase in yield in three regions for 1998 on Bt corn acreage. However, USDA notes that crop yield differences also could be due to other factors not controlled for in their analysis. For example, in one region (Prairie Gateway) USDA reports a 30% yield increase on the Bt corn acreage in comparison to non-Bt acreage. However, there is a significant amount of irrigation in the region. If the majority of the Bt acreage is irrigated also, a yield comparison made to non-Bt acreage that largely may be non-irrigated could show a difference resulting from irrigation practices and not from whether Bt corn was planted.

2.G. Summary

Field corn is the most important crop in terms of value and acreage in the U.S. For 80 years, researchers have been investigating methods of controlling the European corn borer – a non-native insect species that has caused enormous losses in U.S. corn production. Attempts to control the ECB with traditional crop breeding methods and with introduced biological controls have been extensive, but largely unsuccessful. Although the application of chemical insecticides would provide a high degree of ECB control, only a small percentage of corn fields are treated because of the difficulties of scouting for the pest and the precise timing requirements of insecticide applications.

The successful transformation of corn plants with the insertion of a gene from *Bacillus thuringiensis* has produced hybrids with a protein that kills corn borers when they attempt to feed on corn plants. Approximately one-fifth of U.S. corn acreage was planted in 1998 with the Bt hybrids. Since 1998 was a light ECB infestation year and a year of low corn prices, on average, the value of the increased corn yields did not cover the extra cost of the Bt corn seed. However, in most years and, on average, over time, corn growers are expected to more than cover the price premium for the Bt corn seed. In addition, widespread planting of BT corn will mean that the U.S. will no longer annually plant the equivalent of hundreds of thousands of acres of corn that are consumed by the ECB.

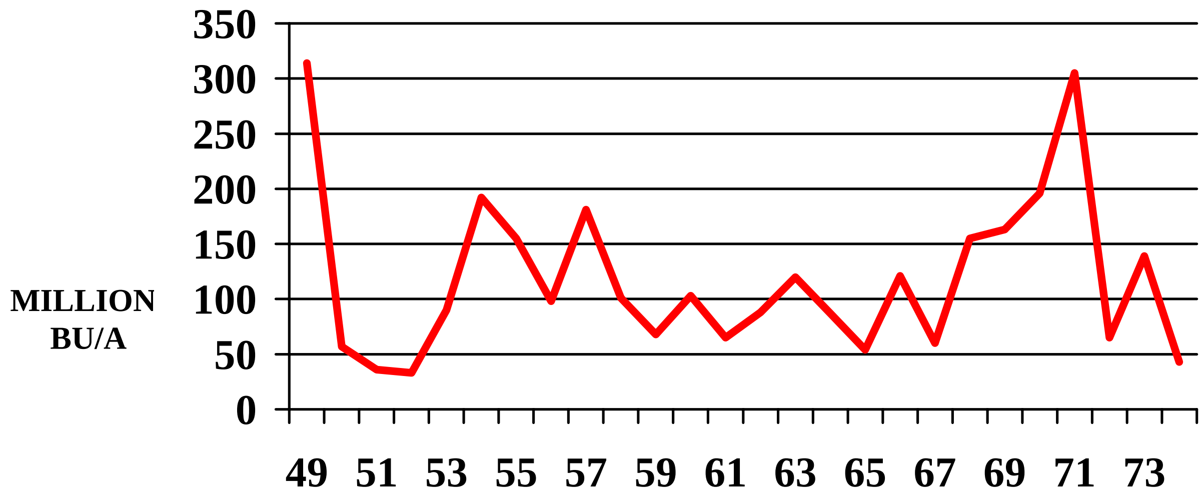
In 1998, the planting of Bt corn seed resulted in a reduction of 2 million acres that would have been sprayed with insecticides for ECB.

TABLE 2.1
Yield Increases from Insecticide Treatment for Second Generation ECB in Iowa

Year	Insecticide	LB AI/A	Bushels Per Acre		Increase	
			Untreated	Treated	Bu/A	%
1991	Methyl Parathion	.75	138	170	32	23
1992	Fonofos	1.00	193	200	7	4
1992	Methyl Parathion	.75	200	209	9	4
1993	Permethrin	.15	115	125	10	9
1993	Chlorpyrifos	1.00	99	114	15	15

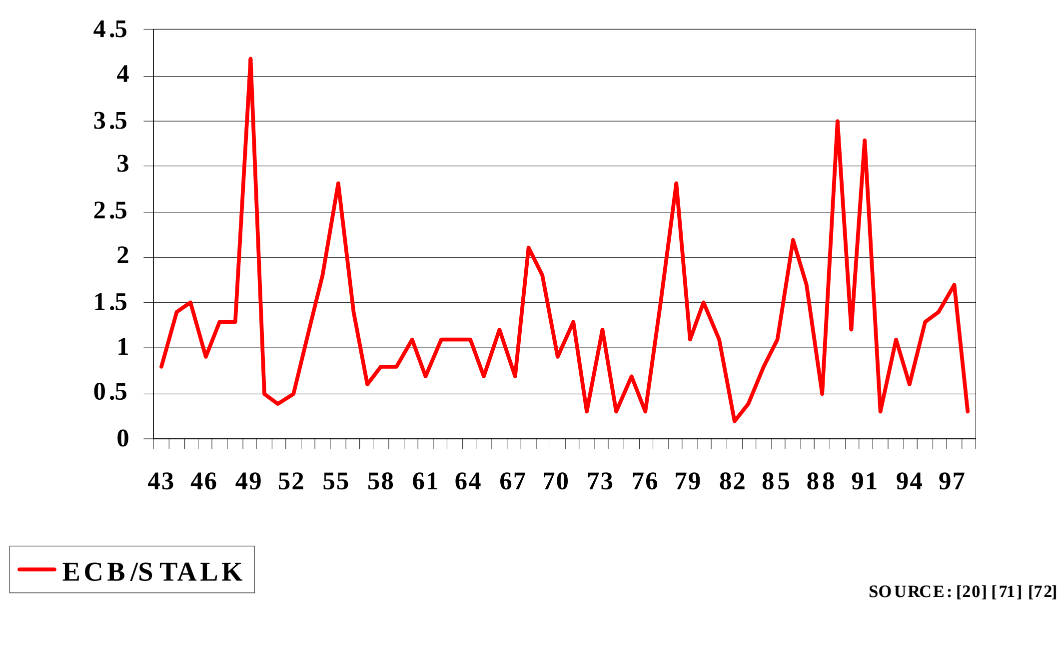
Source: [7] Fields received one insecticide application for second generation corn borer.

FIGURE 2.1
U.S. CORN PRODUCTION LOSSES:
EUROPEAN CORN BORER DAMAGE



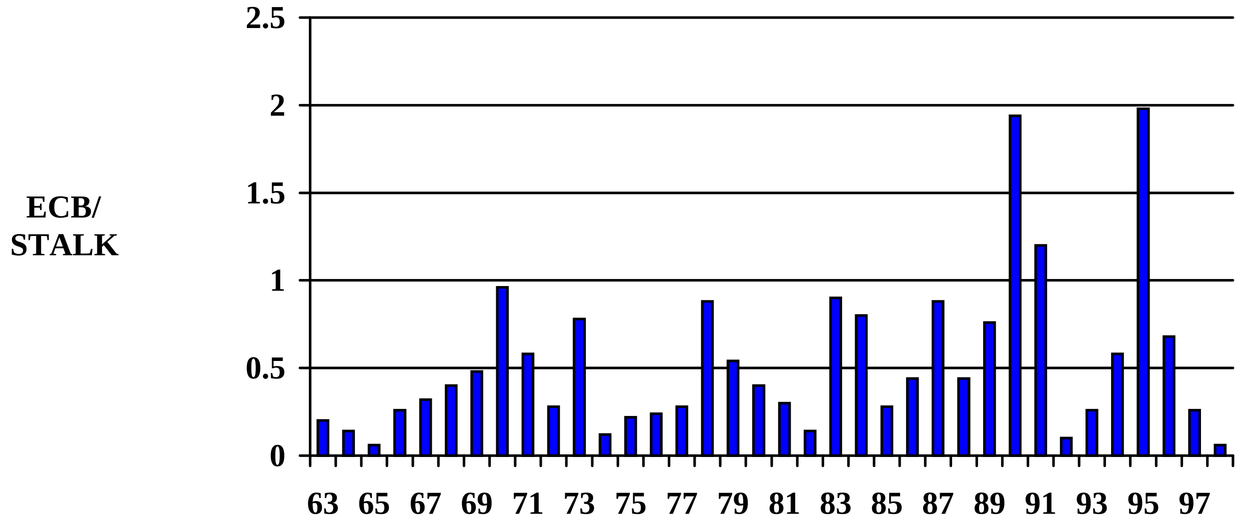
SOURCE: [35] [36] [37]

FIGURE 2.2
EUROPEAN CORN BORER DENSITIES, ILLINOIS 1943-1998



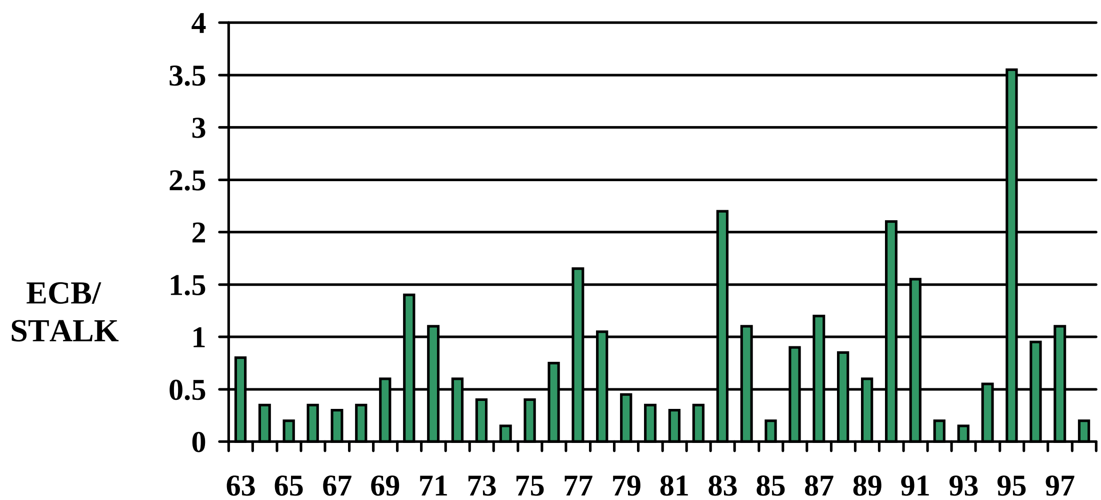
SOURCE: [20] [71] [72]

FIGURE 2.3
WISCONSIN EUROPEAN CORN BORER POPULATIONS



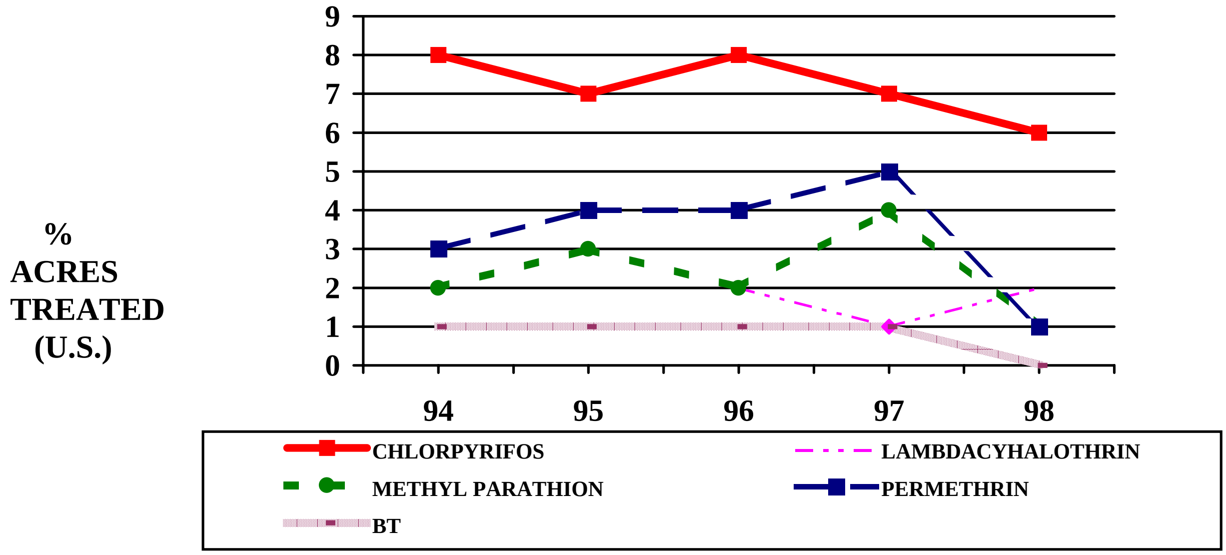
SOURCE: [69]

FIGURE 2.4
MINNESOTA EUROPEAN CORN BORER POPULATIONS



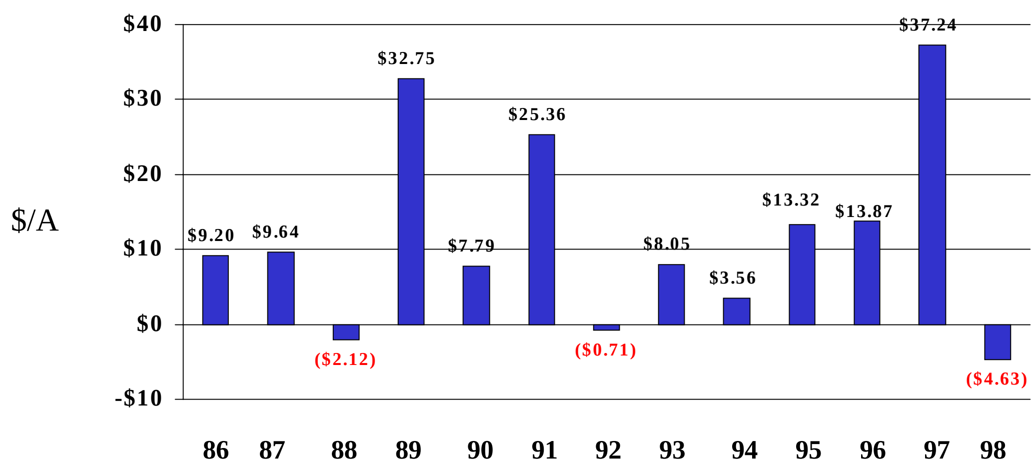
SOURCE: [69]

FIGURE 2.5
INSECTICIDES RECOMMENDED FOR EUROPEAN CORN BORER



SOURCE: [10]

FIGURE 2.6
AVERAGE RETURN FROM BT CORN IN ILLINOIS



SOURCE [72]

3. Cotton

3.A. <u>US Cotton Production</u>

Nearly 14 million bales of cotton were harvested from over 10 million acres in 1998 [116]. Total crop value was over $4 billion in 1998 [87]. The vast majority of this production is upland cotton, while high-quality American-pima cotton, grown primarily in the southwest states, accounted for 442,300 bales in 1998 [116].

Texas is the biggest cotton producing state, accounting for 43% of the total US acreage and 26% of total US production in 1998. Georgia has recently expanded acreage to become the second largest cotton producing state, planting 10% of the US total acreage and accounting for 11% of total production. Several other southern and western states have substantial acreage in cotton production. The top eight states account for over 85% of the total US acreage. Upland cotton production data by state are shown in Table 3.1.

3.B. <u>Insect Pests of Cotton</u>

Each year, cotton growers apply pesticides to control a variety of insect pests that would otherwise reduce yields. The principal pest insects of cotton are those that attack the bolls or the flower buds (squares) that precede them. Insects of secondary importance are those that attack the leaves, stems and planted seeds [127]. In 1998, 71% of the upland cotton acreage was treated with insecticides. The severity of insect pest damage varies from one region to another. In most states, over 90% of the acreage is treated, while in Texas only 47% of the acreage was treated due to low pest pressure in some areas [10].

In 1998, the primary cotton insect pest beltwide was the cotton bollworm, which infested over 9 million acres of cotton and caused a 2.7% yield reduction for the total US crop [122]. Boll weevil was the second most damaging pest, causing 2.3% yield reduction on 5.9 million infested acres. The other most damaging insects include lygus (plant bug), aphids and thrips, while occasional outbreaks of other pests will also cause economic damage to the crop [119]. While damage due to a particular pest varies from year to year, cotton bollworm/tobacco budworm, boll weevil, and plant bugs have dominated the list of the most injurious pests of cotton for the last 20 years [120] [121] [122].

Table 3.1. US Upland Cotton Production 1998

	Acres Planted (1,000)	Yield (lbs./acre)	Production (1,000 bales)
Alabama	495	559	553
Florida	89	489	81
Georgia	1,370	578	1,542
North Carolina	710	699	1,026
South Carolina	290	587	350
Virginia	92	765	145
Southeast	**3,046**	**608**	**3,697**
Arkansas	920	645	1,209
Louisiana	535	586	641
Mississippi	950	737	1,444
Missouri	370	471	350
Tennessee	450	589	546
Delta	**3,225**	**635**	**4,190**
Kansas	17	404	14
Oklahoma	160	560	140
Texas	5,650	524	3,600
Southwest	**5,827**	**524**	**3,754**
Arizona	250	1,177	608
California	650	887	1,146
New Mexico	66	640	80
West	**966**	**949**	**1,834**
US Total	**13,064**	**619**	**13,476**

Source: [116]

Primary insect pest problems vary from one region to another. In several states, such as North Carolina and Georgia, the boll weevil has been eradicated, while in others, such as California, boll weevil was never established. Western growers face different pest problems than other regions. Botton bollworm/tobacco budworm are not a severe problem in California or Arizona. Growers in Arizona, New Mexico, the Imperial Valley of California and Far West Texas are subject to infestations from the pink bollworm, which is not found in other producing areas. Lygus and cotton fleahoppers cause more economic damage in Arizona and California than in other areas [119].

Each year, cotton growers spend approximately $480 million for insecticides and apply approximately 20 million pounds of active ingredient [29] [30].

Genetically altered cotton varieties that incorporate *Bacillus thuringiensis* (Bt) are effective primarily against the tobacco budworm, cotton bollworm and pink bollworm. The following discussion will be focussed on the control of these pests using Bt cotton varieties.

3.C. Tobacco Budworm and Cotton Bollworm

The cotton bollworm was recognized as the chief insect pest of cotton in the late 1800's, as cotton moved into Texas, before the occurrence of the boll weevil, which arrived in the 1890's [126] [127]. Tobacco budworm has become a major pest of cotton more recently. Areas that historically favor high budworm pressure are Alabama, hill areas of Mississippi and regions in Louisiana, south Georgia and the Florida Panhandle.

The cotton bollworm (*Helicoverpa zea*) and tobacco budworm (*Heliothis virescens*) are different insects, but the larvae are identical when observed in the cotton field. These two insects are often referred to as the bollworm/budworm complex, because field identification is nearly impossible until the third instar stage [124]. The life cycle of each insect is similar. Both species overwinter as pupae in the soil and emerge early in the spring to feed on wild hosts and later to infest cotton [125].

Female moths lay 250-1,500 eggs on the upper parts of cotton plants over a period of 3-12 days [124]. Eggs are laid singly, usually in the terminal area and on other tender plant parts. However, eggs may be laid all over the plant, especially on blooms. The eggs are pearly white to a cream color and are about half the size of a pinhead. The eggs hatch into small larvae in three to four days. The life cycle from egg to adult requires about 30 days on average, with the larvae feeding for about 14 to 16 days. The newly hatched larvae first feed on the terminals and younger squares. Larger larvae feed on the terminals and on bolls [123]. The adult worms drop to the ground, burrow into the soil about 2-6 inches and pupate. When they emerge again as moths, they begin another life cycle. There may be as many as three or four generations per season [124].

Cotton is less susceptible to yield loss from bollworm/budworm before the cotton plants begin blooming than later in the season when the second and subsequent generations occur [7]. Feeding damages or destroys the squares, blooms and bolls. Injured squares flare and drop from plants usually within 5 to 7 days. Large larvae feed on bolls, squares and pollen in open flowers. They may even devour the contents of large bolls. Worm-damaged bolls frequently are lost to boll rot even if not eaten completely. Larvae may "top" young plants by devouring the terminal. This often delays plant growth and may cause abnormal, nonproductive growth [131].

The cotton bollworm is known by several other common names, as it infests many other crops besides cotton. It is the same insect as the corn earworm. In areas where both cotton and corn are grown, this insect prefers corn, and only moves into cotton fields after the corn crop begins to dry down.

3.D. Pink Bollworm

The first infestation in North America by the pink bollworm (*Pectinophora gossypiella*) was reported in Mexico in 1916, presumably introduced through cotton seed shipments from Egypt. Pink bollworm infestations were found the following year in Texas, imported from Mexico also on cotton seed shipments. By 1926, the pink bollworm had spread from Texas through New Mexico and into eastern Arizona. Although eradication was declared in Arizona in 1934, 1938 and 1946, the pink bollworm eventually spread across Arizona and into Southern California by 1965 [128]. Pink bollworm has been unable to establish economically damaging populations in the mid-south and southeastern regions of the country despite infrequent outbreaks in Florida, Georgia, Louisiana and

Missouri. However, environmental conditions in states across the cotton belt are considered likely to support reproduction and survival [129].

Pink bollworm is a major pest of cotton in Southern California deserts, Central and Northwestern Arizona, New Mexico and Far West Texas. The Imperial Valley of California had a peak in cotton acreage of approximately 58,000 hectares in 1977 and averaged near 35,000 hectares from 1978-1981 [128] but has declined rapidly since to about 7,800 hectares in 1998 [122]. This decline has been due to increased costs of controlling the pink bollworm and to declining commodity prices [128].

Pink bollworm eggs are greenish-white and are laid on the stems and squares and occasionally on terminal buds [132]. They are most often found between the calyx and boll wall. Eggs are usually deposited singly and normally hatch within 4 to 5 days. Developing larvae bore into and feed on the developing flower or into a boll to feed on the seed. Larvae feed for 10 to 14 days. They usually leave the fruit and pupate in the soil, taking about 8 days to transform into an adult. In late summer and fall many larvae do not pupate immediately upon completion of the feeding period but remain inside the boll. These are the overwintering stages that give rise to the first generation the following season [131].

Damage is caused in the late season, as developing larvae tunnel through the boll wall and then lint fiber as they move from seed to seed. Larvae feed on squares in the early season without economic damage to the crop [130]. But once bolls are present, they become the preferred food supply. The burrowing activity stains lint, destroys fibers and reduces seed weight, vitality and oil content. Pink bollworms cut holes in boll walls as they leave bolls for pupation. These holes may become infected with boll-rotting organisms. During severe infestation, many bolls that might otherwise have been harvested are rendered unpickable [131] [132].

3.E. Historical Control Methods

The importance of various insects in cotton production has shifted over time, depending on the availability of effective insecticides, as well as some unintended effects of insecticides on non-target insects.

In the early 1900's, the control of insects in cotton was achieved primarily through the use of cultural and physical control methods. Boll weevil became the primary pest of cotton after it was introduced in the 1890's and the available insecticides, such as Paris green and lead arsenate, did not provide effective control against this pest [126] [133]. Early maturing or shorter season cotton varieties were grown in order to limit damage by late-season boll weevil attacks than in the more indeterminate, longer-season cottons. When combined with the early fall destruction of the harvested cotton plants, this system allowed a means of profitably growing cotton with only minimal use of insecticides. However, the staple length of the shorter-season cottons was inferior to that of the longer-season cottons, which meant lower prices for farmers [127].

In 1918, calcium arsenate was shown to provide effective control of boll weevil, thus providing growers an alternative to non-chemical control methods. Aerial application methods were developed shortly thereafter, and this method of application became widespread [134]. Nonetheless, many growers continued to rely upon non-chemical control methods until the organochlorines were introduced after World War II [127]. Some growers achieved poor results using calcium arsenate, presumably due to poor timing of applications. During this period, the concept of scouting for proper treatment timing was emerging. Researchers found that automatic early season application of calcium arsenate failed to control weevils or increase yields, while treating emerging 1st generation adults was quite effective [133].

In the late 1940's and early 1950's, highly effective organochlorine insecticides became available that controlled all of the serious pest insects of cotton, though no one material would control all the arthropod pests of cotton. The organics produced more effective insect control, and higher yields, than inorganic insecticides, such as calcium arsenate [127]. As a result, considerably more cotton acreage was being treated with insecticides than ever before, and organochlorine compounds largely replaced calcium arsenate [134]. Some of these new materials were DDT, benzene hexachloride, toxaphene, chlordane, and methoxychlor [127] [134] [135].

The availability of relatively low-cost, effective chemical insect control allowed growers to realize greater benefits from fertilizer and irrigation inputs, and began a period of concerted effort to maximize yields. During the 10 year period from 1936 to 1945, which preceded the first wide-scale use of organochlorine insecticides in 1946, cotton yields averaged about 251 lbs. of lint cotton per acre. This compares to average yields of about 300 lbs. of lint cotton per acre, or 16 % more, during the first 10 years, 1946 to 1955 that DDT and other organic insecticides were used extensively [127]. In addition, the new insecticides made it possible for growers to use longer season varieties with higher-quality, longer-staple lint, due to their ability to protect plants from weevil damage through an extended fruiting period [127].

The development of insect resistance to organochlorine insecticides reduced the effectiveness of these materials and led to introduction of new classes of insecticides for cotton insect control. Organophosphate and carbamate insecticides were developed that provided highly effective control of the boll weevil but were not so effective against bollworm/budworm. The organophosphates became most widely used to control boll weevils resistant to organochlorine insecticides. However, their use resulted in the destruction of natural parasites and predators of bollworm/budworm. As the use of organophosphates increased, the boll weevil faded in importance and bollworm/budworm became the pests of primary concern in cotton production. Additional insecticides were necessary to control outbreaks of bollworm/budworm in areas infested with the boll weevil [127]. Synthetic pyrethroids were introduced in the late 1970’s, offering growers effective insect control with materials that were applied at low rates [135].

No other class of insecticides had before, or since, equaled the pyrethroids for economic control of the bollworm/budworm complex. As exceptional as these compounds are, as early as 1977, laboratory studies showed increased tolerance to the pyrethroids in assorted insect strains. The expression of pyrethroid resistance was first reported in the US from isolated areas of west Texas in 1985. These failures, though isolated, demonstrated the need for bollworm/budworm population monitoring and the judicious use of pyrethroids to preserve the usefulness of these highly cost effective larvicides [161]. The introduction of pyrethroids is credited with allowing the expansion of cotton production in areas such as South Carolina because growers were getting poor control of budworm and bollworm previously [160].

Problems with insect resistance to insecticides, resurgence of secondary pests, and regulatory actions limiting availability of some widely used cotton insecticides such as DDT, led to renewed emphasis on integrated pest management and total population management ideas during the late 60's and into the 70's [126]. In particular, boll weevil eradication was being pursued by USDA, with the first large scale trial beginning in North Carolina in 1978 [126]. Under boll weevil eradication, the use of insecticides that were harming beneficial insect populations that could provide natural control of bollworm/budworm could be drastically reduced. By 1998, boll weevil erdication had been achieved on more than 4.7 million acres in 11 states, and was underway on 2 million more acres [136].

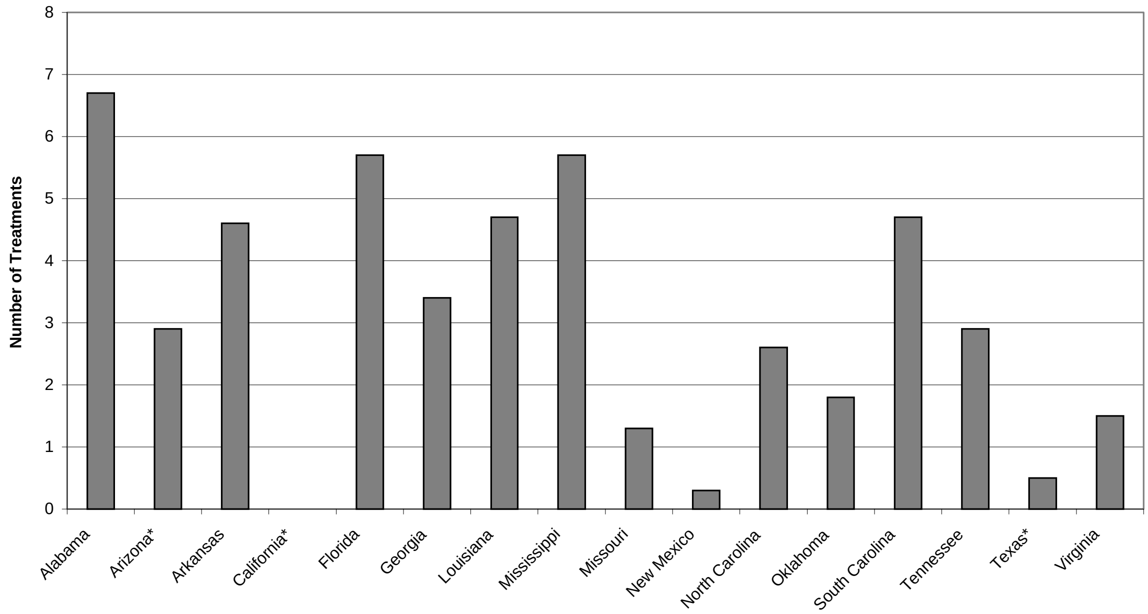
Control of the pink bollworm has a shorter history than the bollworm/budworm. Although it first became established in Texas in 1922, it did not become a serious pest until the 1950's. Harvest-aid chemicals and mechanical harvesting resulted in effective cultural control of this insect in those parts of Texas where it had been a serious pest. In the mid-1960's, the pink bollworm invaded California and Arizona, where climate favors long-season cotton production. In these areas, large quantities of organophophate insecticides were used to control the pink bollworm. By the late 1960's, these areas had the highest per acre cost for cotton insect control in the US [126].

3.F. Insect Control in Conventional Cotton

Two regularly conducted surveys provide information on insecticide use by cotton growers. The first survey is coordinated through extension agents in cotton producing states and relies on information provided by county agents, extension specialists, private consultants and research entomologists. This survey is supported by the Cotton Foundation, and the results are presented each year in the Beltwide Cotton Conference Proceedings [120]. Information collected includes data on infestation by various insect pests, number of insecticide treatments targeted at various pests, and yield losses due to insects. The second survey is conducted by the USDA National Agricultural Statistics Service (NASS) and reports treated acreage and amount of insecticide used by state, but does not indicate target pests [10].

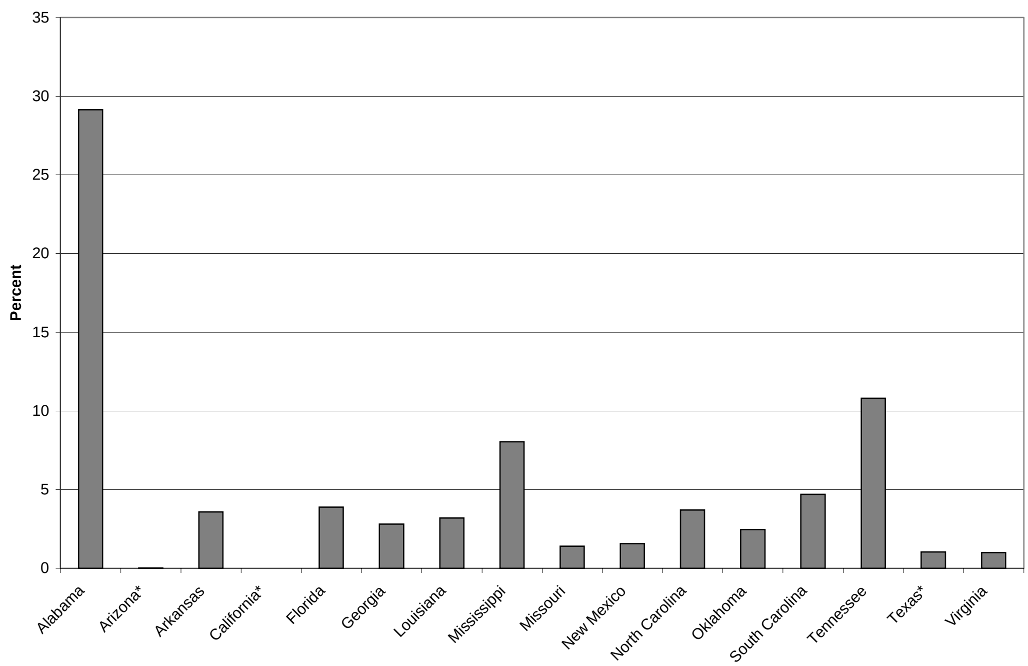
In 1995, the year before Bt cotton varieties were introduced, the Cotton Foundation survey estimated that an average of 2.4 insecticide applications were made to control bollworm/budworm across all cotton producing states, and that a 3.97% yield loss was incurred due to these two pests. Severity of infestations and the resulting level of insecticide use varied across areas. Figure 3.1 shows the number of insecticide treatments that were targeted at tobacco budworm, cotton bollworm and pink bollworm across the cotton belt in 1995. Tobacco budworm infestations were particularly heavy in 1995, causing severe yield losses in some areas. The worst damage was sustained by Alabama growers, who on average experienced a 29% yield loss. Tennessee also experienced higher than normal yield losses of 11% [148]. Figure 3.2 shows yield losses due to tobacco budworm, cotton bollworm and pink bollworm in 1995.

Figure 3.1
Insecticide Treatments Targetted at Tobacco Budworm, Cotton Bollworm and Pink Bollworm
1995



Source: [120]

Figure 3.2
Yield Losses Due to Tobacco Budworm, Cotton Bollworm and Pink Bollworm in1995



Source: [120]

The NASS survey data provides information on specific insecticides used by cotton producers. However, determining which pests various insecticides were targetted at is problematic, since many materials have activity on more than one pest. A review of insect control guides for several states was performed to identify the materials that are recommended for budworm and bollworm control. Insecticide use data for those materials believed to be used most frequently for bollworm/budworm control are provided in Table 3.2. Most of the bollworm/budworm insecticides are targetted at controlling larvae (larvicides). Amitraz, methomyl, and thiodicarb target the egg stage (ovicides).

Several of the commonly used insecticides for bollworm/budworm are pyrethroids, e.g. bifenthrin, cyfluthrin, cypermethrin, esfenvalerate, lambda-cyhalothrin and tralomethrin. While these materials are preferred for bollworm/budworm control because they are cheaper than other insecticides, the development of pyrethroid-resistant budworm populations has diminished their usefulness in recent years. In Louisiana during 1998, survival rates in adult vial testing ranged from 41% in May to 60% in June [162]. In Arkansas, pyrethroid resistance by the tobacco budworm has progressed to the point of basically no control in 1998 [163].

Indeed, the severe budworm problems experienced by Alabama growers in 1995 were due to the ineffectiveness of the pyrethroids in face of high levels of budworm resistance. Many farms yielded less than 200 pounds of lint per acre and numerous fields were plowed under without harvesting [139]. Pyrethroid resistance is more of a problem in the mid-south and Texas than in the southeastern states. In North Carolina, pyrethroid resistance in cotton bollworm and tobacco budworm is just now being detected [137].

In some areas of the US, the resistance spectrum of tobacco budworm continues to expand and now encompasses many of the newer organophosphate and carbamate insecticides [140]. The documentation of pyrethroid resistance by tobacco budworm in Arkansas, Louisiana, Mississippi and Texas has led to the development of several insecticide resistance management plans. A major component of these resistance management plans is the alternation of the Bt products, carbamates, organophosphates and pyrethroids during different stages of the cotton growing season. However, the budworm has already demonstrated the ability to develop resistance to selected OP's and carbamates, if enough selection pressure is exerted. In 1990, resistance to the selected organophosphates and carbamate insecticides was confirmed in budworm populations in Louisiana and Mississippi [141]. Broad spectrum resistance to insecticides limits growers options to control the budworm.

Insecticide resistance in cotton bollworm populations has already shown signs of development as well, though not to the extent of the budworm [162] [163]. Cotton bollworm moth survival in adult vial testing for pyrethroid resistance in Louisiana showed a dramatic increase in resistance in 1998 [162].

Table 3.2. Cotton Bollworm/Budworm Insecticide Use in 1995

Insecticide	Percent of Acres Treated
Amitraz	4
Bifenthrin	6
Bt	9
Cyfluthrin	12
Cypermethrin	12
Esfenvalerate	7
Lambda-cyhalothrin	21
Methomyl	9
Profenofos	13
Sulprofos	2
Thiodicarb	12
Tralomethrin	7

Source: [10]

In Southern California, an area wide program went into effect in the Imperial Valley in 1989 to control pink bollworm. This program mandates the use of a defoliant or plant growth regulator at the beginning of September, and plowdown of shredded plant stalks after harvest at the beginning of November [138]. Shredding destroys some larvae directly and promotes rapid drying of unharvested bolls [132]. The program also changes cotton growing in the Imperial Valley from full to short season management systems. Such practice changes have been effective in reducing pink bollworm populations [138].

3.G. Alternatives

As resistance to available insecticides has developed, researchers have sought alternative insect control methods.

Conventional insecticides will likely continue to be relied upon in integrated pest management programs of the future. With development of insect resistance to “old” chemical groups, novel conventional insecticides with new modes of action are of particular interest.

One new class of insecticides is the spinosyns, which are derived by the fermentation of the metabolites of a species of Actinomycetes. Spinosad (Tracer) is a recently commercialized insecticide in this class for use in cotton. It is effective against a range of insect pests, including tobacco budworm and cotton bollworm, while remaining relatively safe for most beneficial insects [164] [173]. Spinosad was applied to 4% of the cotton acreage in 1998 [10]. Limited availability and difficulty with proper timing of application for effective control have hindered adoption of this product [165].

Chlorfenapyr (Pirate) is from another class of insecticides, the pyrroles, which are developed from a strain of Streptomyces. It has become available on a limited basis through a Section 18 in some parts of the US and has activity against a broad spectrum of pests including bollworm and budworm [164]. Chlorfenapyr was used on 2% of the US cotton acreage in 1998 [10].

Products from two other classes of insecticides have also been identified as having potential uses in cotton production. Indoxacarb (Steward) in an oxadiazine, with good larvicidal activity, high selectivity and little impact on beneficial insects. Methoxyfenozide (Intrepid) is a diacylhydrazine, representing a new generation of insect growth regulators. This product disrupts molting in a range of Lepidopteran pests and causes minimal disruption of beneficial insects [164].

Foliar applied formulations of *Bacillus thuringiensis* have also been used for the control of budworm and cotton bollworm in cotton production, though its use has declined since the introduction of Bt cotton varieties. In 1995, 9% of cotton acreage was treated with Bt products, while in 1998, Bt was applied to only 1% [10]. Part of this reduction is likely due to the restriction on the use of Bt products in refuge areas that are part of resistance management programs for Bt cotton varieties.

Non-conventional approaches to management of the tobacco budworm, cotton bollworm and pink bollworm have also been pursued. One such approach is the use of sterile insects. Sterile insect technology has been used successfully for over 25 years to prevent the establishment of pink bollworm in the San Joaquin Valley of California. The feasibility is based on the ability to achieve a sufficiently high ratio of sterile insects over a relatively small migratory population. This technology has been tested on a large scale in the Imperial Valley. In combination with the use of pheromones, the sterile insect technology has allowed the extension of the season and brought populations down below the economic threshold [166]. The release of sterile tobacco budworm has also been tested in the central Delta of Mississippi. However, in a pilot program the spring release of sterile insects was not shown to reduce the July tobacco budworm population [167].

Another non-conventional approach to the control of tobacco budworm, cotton bollworm and pink bollworm is the use of pathogens. A baculovirus from the cotton bollworm has been registered by the Environmental Protection Agency for use in row crops. The virus occurs naturally in the Delta of Mississippi, where its use has been tested, and is known to infect only insects in the Heliothis/Helicoverpa genera. The negative aspects of the baculoviruses include their slow activity and problems related to in-field persistence of the virus. Collective results of studies conducted over an 11 year period indicate that virus application to the weeds that host bollworm/budworm prior to crop emergence can be accomplished at a reasonable cost and that such treatment consistently reduced the number of moths emerging from weed hosts by over 70% [168]. A second virus, isolated from the celery looper, has also been shown to be highly infectious to bollworm/budworm, and to have potential as a microbial control agent for control of these pests [169].

3.H. Bt Cotton

Transgenic cotton carrying the insect-resistant Bt gene was commercialized in 1996. The method used to insert the Bt gene into cotton is different than that used for corn. For cotton, the Bt gene was first introduced into a soil-borne bacterium *Agrobacterium tumefaciens*, which normally infects wound sites of a plant and transfers a segment of a plasmid into the plant cell. Hormone genes located in a portion of the plasmid are integrated into the plant chromosome. Subsequent expression of the hormone genes results in cell proliferation. This ability of *A. tumefaciens* to transfer DNA into plant cells can be exploited to transform plants with useful genes, by inserting the genes of interest into the DNA that are then transferred to the plant cells [142].

Field tests confirmed that plants expressing these modified genes were capable of providing effective control of tobacco budworm, pink bollworm and of moderate levels of bollworm [143]. Bt cotton plants were shown to be highly toxic to first to fourth instars of bollworm and tobacco budworm, but not to fifth instars [147]. Four years of field testing in Mississippi showed that Bt cotton prevented crop failure when tobacco budworm populations were high [144].

Bt cotton represented the first true larvicide for pink bollworm. Conventional controls historically targeted the non-damaging stage of pink bollworm, the moth [145]. In tests that evaluate the survival of fourth instar larvae of pink bollworm, numbers of larvae in the Bt cotton fields were extremely low or zero, even in fields adjacent to heavily infested control fields [146].

Efficacy ratings for Bt cotton against various pests are shown in Table 3.3. It should be noted that the Bt cotton varieties do not completely control the cotton bollworm, which may reach economic thresholds and require spraying.

Table 3.3. Level of Control of Cotton Pests by Bt Cotton in Research Plots

Species	**% Control**
Tobacco Budworm	95
Cotton Bollworm pre-bloom	90
Cotton Bollworm blooming	70
Pink Bollworm	99
Cabbage looper	95
Beet Armyworm	25
Fall Armyworm	20 or less
Saltmarsh Caterpillar	85 or more
Cotton Leaf Perforator	85 or more
European Corn Borer	85 or more

Source: [171]

The adoption of Bt cotton varieties was extremely rapid in some areas and has been slower in others. Overall, Bt cotton was planted on 14% of US cotton acreage in the first year it was available. Adoption has been steadily increasing, to 16% in 1997 and 17% in 1998 [122] [114].

After a year of very high budworm populations and damage in 1995, growers in Alabama adopted Bt varieties at an extremely rapid rate, planting 80% of acreage to Bt varieties in 1996 [148]. In 1996, growers faced high infestations of bollworm, which is not as effectively controlled by Bt varieties as the budworm. The next year, adoption rates in Alabama dropped to 53%, but have since rebounded to 63% in 1998 [171].

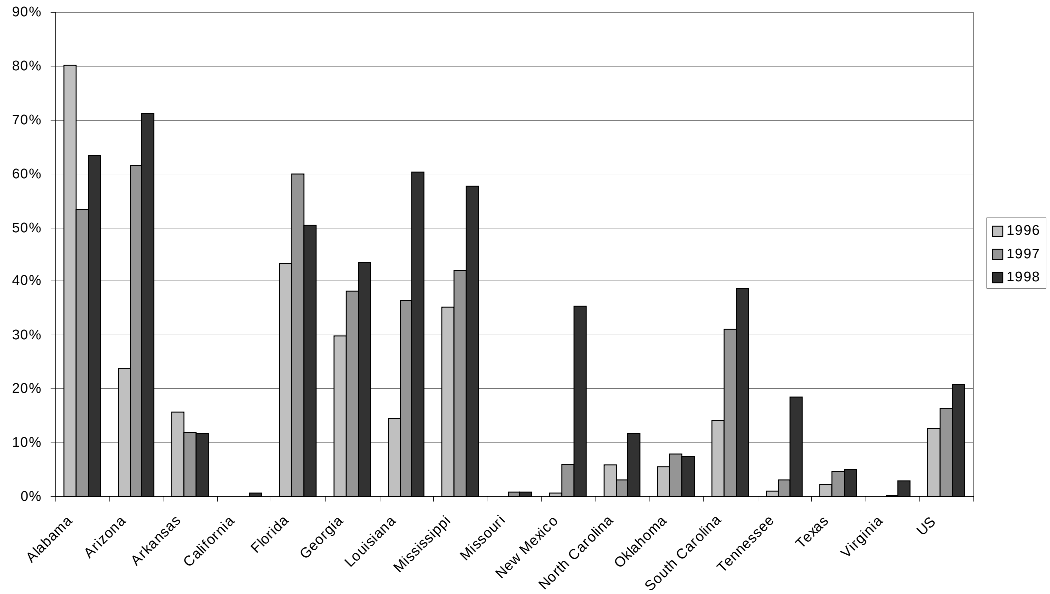
Arizona also had very high adoption rates, with growers planting over 70% of their acreage to Bt varieties in 1998 [122]. Some of this acreage is grown under contract for seed production for the companies supplying Bt seed to growers [175].

Two major cotton producing states have had very low adoption rates thus far. Texas, by far the largest cotton producing state, has adopted Bt cotton on a small scale, accounting for only 5% of total cotton acreage in 1998 [122]. This is partially due to the unavailability of varieties appropriate to the climate in many areas of that state, where "stripper" varieties that hold lint tightly are needed for storm-proofness. Also, much of the production in Texas is dryland and the Bt technology is considered too expensive [149].

California is another large cotton producing state with low adoption rates. A 73 year old law, the One-Quality Cotton District law, had until recently required three years of variety testing before any variety could be planted in the state. This law was changed for the 1998 growing season to allow new varieties, including transgenic varieties, to be planted. However, the demand for Bt varieties in California is not expected to be as high as in other areas of the country because most cotton producing areas of California do not have the pests that Bt varieties control [150]. Figure 3.3 shows Bt variety adoption rates by state for 1996-1998. Figure 3.4 shows the patterns of adoption in 1998 throughout the cotton belt.

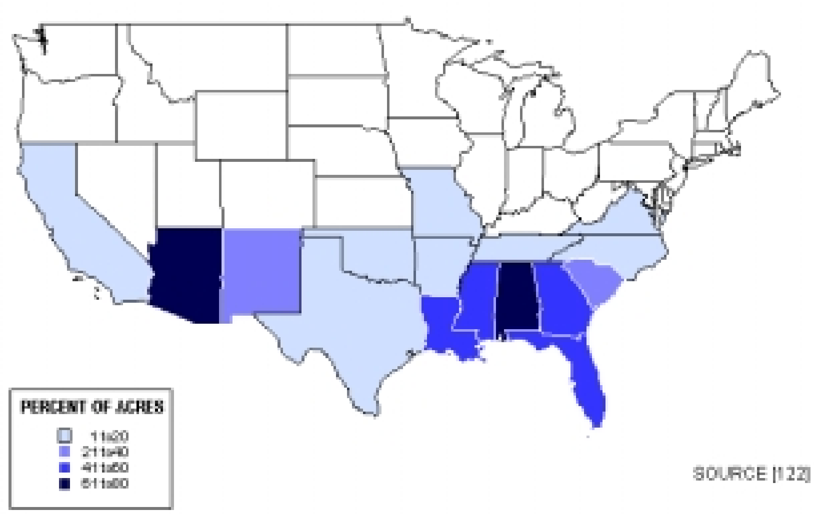
Growers who plant Bt cotton varieties are required to plant a portion of their acreage to non-Bt varieties in order to manage the development of resistance to Bt in pest populations. The refuge requirements vary depending on whether the grower plans to apply insecticides to the refuge to control the target pests of Bt cotton. If a grower is planning to spray the refuge, then a ratio of 100 acres of Bt cotton to 25 acres of non-Bt cotton is required. If a grower does not treat the refuge with insecticides that control the target pests of Bt cotton, a ratio of 100 acres of Bt cotton to 4 acres of non-Bt cotton must be maintained. These refuges should be in proximity to the Bt cotton fields [172].

Figure 3.3
Percent of Cotton Acreage in Bt Varieties



Source: [120] [121] [122]

FIGURE 3.4
ACREAGE PLANTED TO BT COTTON
1998 (%)



3.I. Impact of Introduction of Bt Cotton Varieties

The adoption of Bt cotton varieties is expected to reduce the amount of insecticide used in cotton production, reduce insecticide costs and increase yields, as growers face reduced pressure from budworm, bollworm and pink bollworm.

The number of insecticide treatments targeted at the tobacco budworm, cotton bollworm and pink bollworm is expected to decline as Bt cotton varieties are adopted. An annual survey conducted by extension agents in cotton producing states provides data on the number of insecticide treatments per acre by target pest. Table 3.4 shows the number of insecticide treatments targeted at budworm, bollworm and pink bollworm for the major adopting states since 1986. These data show a reduction in the number of insecticide treatments for the pests that Bt cotton varieties control since 1996 when Bt varieties were introduced.

Insecticide usage in cotton would also be expected to decrease as more acreage is planted to Bt cotton varieties. Insecticide usage data in cotton is available from the USDA National Agricultural Statistics Service (NASS). Insect control recommendations from several cotton producing states were used to identify the insecticides that growers were likely to use to control the target pests of Bt cotton. The use of these insecticides was compared for 1995, the year before Bt cotton varieties were introduced, and 1998. The difference in use was adjusted to account for reduction in planted acreage from 1995 to 1998. The results of this calculation are presented in Table 3.5. As can be seen, the overall reduction in insecticide use for bollworm/budworm is estimated at 2.0 million pounds, or 12% of all insecticides used in those five states in 1995.

Table 3.4. Number of Insecticide Treatments in Cotton for Bollworm/Budworm (Pink Bollworm in Arizona)

	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
Alabama	5.5	4.9	2.1	4.0	2.5	2.9	2.9	4.8	4.4	6.7	0.1	0.5	1.4
Arizona	1.7	5.8	2.5	3.2	2.5	6.8	1.1	0.1	2.9	2.9	1.7	0.9	0.4
Florida	9.0	7.1	5.6	8.4	7.2	5.0	5.0	5.3	5.3	5.7	1.1	1.0	2.0
Georgia	7.3	6.2	4.4	4.3	5.0	4.9	3.4	2.7	4.3	3.4	1.7	2.5	1.5
Louisiana	5.5	4.3	3.7	5.8	5.0	3.5	5.8	4.7	4.8	4.7	3.9	3.2	3.5
Mississippi	4.3	4.5	3.6	4.3	3.4	1.5	5.1	4.3	4.1	5.7	2.2	2.5	2.5

Source: [170]

Table 3.5. Cotton Bollworm/Budworm Insecticide Use Reductions After the Introduction of Bt Varieties

Insecticide	**(1,000 lbs.)**
Amitraz (Ovasyn)	42
Cyfluthrin (Baythroid)	35
Cypermethrin (Ammo)	81
Deltamethrin (Decis)	-11
Esfenvalerate (Asana)	19
Lambdacyhalothrin (Karate)	58
Methomyl (Lannate)	156
Profenofos (Curacron)	1,014
Spinosad (Tracer)	-19
Thiodicarb (Larvin)	665
Tralomethrin (Scout)	4
Zeta-cypermethrin (Fury)	-1
TOTAL	**2,044**

(AR, AZ, LA, MS, TX)

It must be recognized that there are other factors that may have contributed to changes in both the number of insecticide treatments and the amount of insecticides used for tobacco budworm, cotton bollworm and pink bollworm. First, in many cotton producing areas, boll weevil eradication programs have been pursued. In areas where the weevil has been eradicated, the return of beneficial insects that naturally control bollworm/budworm should have reduced the number of treatments needed for control of these pests. This would overstate the impact that adoption of Bt varieties has had on insecticide use.

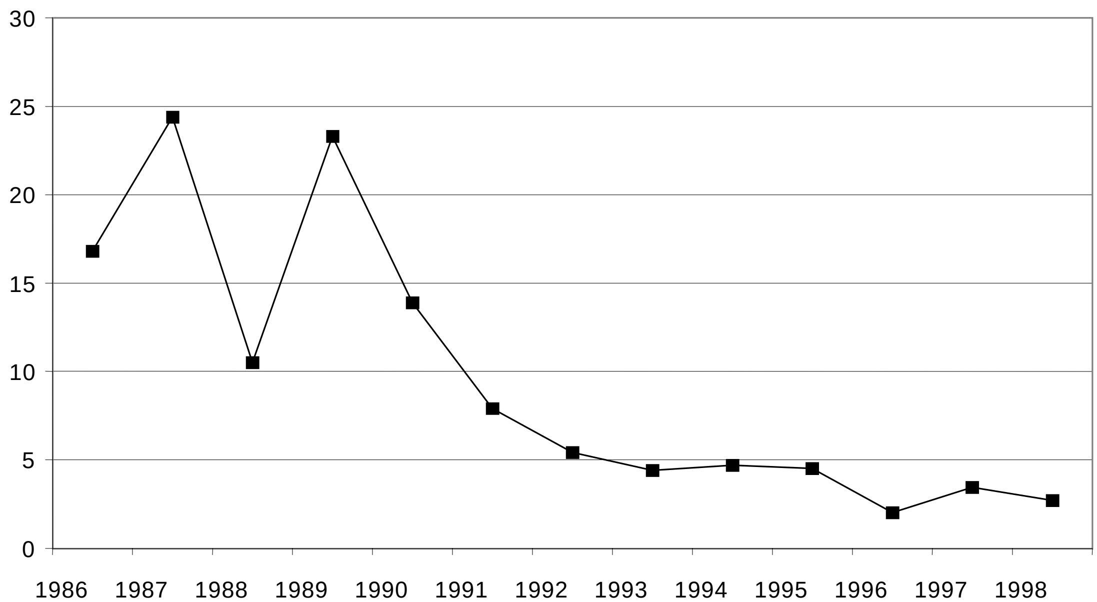
Georgia provides a good example of an area that had completed boll weevil eradication several years before Bt cotton varieties were introduced, allowing a clearer view of the impact of adoption of Bt varieties. The average number of treatments towards bollworm/budworm between 1991 and 1995 was 3.74 compared to 1.9 from 1996 to 1998 [170]. (See Table 3.4.) It is also interesting to look at total number of insecticide treatments in light of boll weevil eradication and introduction of cotton varieties. Figure 3.5 shows the total number of insecticide treatments in Georgia from 1986 to 1998. Boll weevil eradication began in Georgia in 1987 and was completed in 1991. The total number of treatments was high during this period, driven in large part by the number of treatments directed towards boll weevil. In 1987, an average of 16.6 treatments were directed at boll weevil. In 1989, 13.1 treatments were made toward boll weevil control [170].

Second, the insecticides that were being used to control these pests were also controlling other secondary pests. With a reduction in the number of treatments towards tobacco budworm, cotton bollworm and pink bollworm, populations of these secondary pests have increased. Indeed, increasing populations have been reported in several areas for secondary pests such as tarnished plant bug, stink bugs and fall armyworms, as well as boll weevil in some areas [144] [151] [152]. In some cases, economic thresholds did not exist for these pests, since they had not been a problem previously [165]. Researchers have been working to develop thresholds for their control since the introduction of Bt cotton varieties [174]. However, some growers have probably increased the number of treatments targeting these pests.

To the extent that growers have increased the use of the insecticides identified above, this increase is taken into account in the calculation of the reduction in pesticide use. Usage of three of the insecticides that were identified as targeted towards bollworm/budworm (deltamethrin, spinosad and zeta-cypermethrin) increased between 1995 and 1998, likely due to increased treatments for other pests or the substitution of one insecticide for another. (See Table 3.5.) If growers are using other materials to control these pests, then those increases in pesticide use are not included in the calculation and the impact that the adoption of Bt varieties has had on insecticide use is again overstated.

Finally, reduced insecticide use on acreage planted to Bt varieties allows populations of beneficial insects to increase, suppressing population of other pests such as aphids, whiteflies, mites, beet armyworms and loopers [153] [154]. If growers have reduced their use of insecticides other than those included in the above calculation for control of these pests, then the calculation of reduction in insecticide use is understated.

Figure 3.5
Number of Insecticide Treatments for All Insect Pests in Georgia Cotton



Source: [170]

Adoption of Bt varieties is also expected to increase yields through better pest control and avoidance of crop damage. Table 3.6 charts the losses by state due to bollworm/budworm before and after the introduction of Bt cotton. Though not as dramatic as the reduced insecticide use, in some cases, such as Louisiana and Florida, the reduction in yield losses due to bollworm/budworm is clear.

These general trends in insecticide usage and yields has been shown in field studies conducted in several states.

In three years of field use in North Carolina, 307 fields of Bt cotton were compared to 307 fields of conventional cotton. The Bt fields averaged 0.77 applications of insecticides while conventional fields were treated 2.65 times. The Bt fields sustained only 40% as much boll damage from bollworms as the conventional fields, while stink bug damage was approximately four times higher than in the conventional fields [155].

Table 3.6. Yield Losses Due to Tobacco Budworm and Cotton Bollworm (Pink Bollworm in Arizona)

	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
Alabama	2.6	4.6	4.4	2.6	3.0	1.4	1.7	2.5	6.8	6.1	29.1	3.1	3.2	4.7
Arizona	1.0	0.3	0.2	0.2	0.2	0.2	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Florida	4.3	5.5	7.2	4.4	5.5	9.1	4.0	3.0	3.0	3.7	3.9	3.3	4.3	2.1
Georgia	3.6	4.1	2.1	2.7	4.7	5.0	1.0	1.8	1.9	1.9	2.8	1.9	2.5	2.8
Louisiana	4.0	5.3	2.7	2.3	5.8	4.0	3.5	7.5	3.6	2.9	3.2	2.3	1.9	1.5
Mississippi	1.3	4.4	4.3	4.6	4.3	4.5	0.6	3.9	3.9	4.1	8.0	1.9	2.4	4.2

Source: [170]

A Mississippi field survey found that Bt fields sustained significantly less caterpillar induced boll damage and received significantly fewer foliar insecticide treatments for control of bollworm and tobacco budworm, 1.22 vs. 5.18, compared to fields planted to conventional varieties [156].

Alabama growers went from the worst year on record for cotton insect losses in 1995 to the lowest amount of insecticide applications and usage since the introduction of synthetic insecticides in the 1940's. Less than 20% of the total cotton acreage in Alabama received any foliar insecticides in 1996. Less than 10% of the Bt acreage was treated a single time [139].

In a study of the impact of Bt variety adoption in the Southeast, researchers found that yields were higher, insecticide use was lower and profits were higher for Bt adopters than non-adopters. Approximately 300 growers in Alabama, Georgia, South Carolina and North Carolina were surveyed for information about the 1996 growing season. Adoption in the area was 22% of total acreage. Average yields reported were 11.4% higher in fields planted to Bt varieties than conventional varieties. Insecticide application per season were 72% lower and profits from Bt cotton adoption were $51 per acre higher [157].

In a survey of 109 sites in Southern and Southeastern states in 1998, growers, consultants and university/extension researchers kept records of costs and yields of Bt and nearby, similarly managed non-Bt fields. Over all sites, yields on Bt fields were 37 lbs. higher for Bt varieties. Though the overall number of insecticide applications required on Bt fields was lower than in conventional fields, the number of insecticide application for pests not controlled by Bt varieties was higher. Overall insecticide control costs were still $15.43 lower on Bt fields, including the technology fee. The economic advantage of Bt varieties was approximately $40 per acre [159]. Table 3.7 shows the results of the survey.

Table 3.7. Summary of 1998 Survey of Southeastern Cotton Growers (Per Acre)

	Conventional Variety	**Bt Variety**
No. BW/TBW Sprays	5.3	1.4
Cost for Single BW/TBW Spray	$9.64	$7.13
Total BW/TBW Insecticide Cost	$54.93	$9.96
Total No. of All Insecticide Applications	8.3	6.0
Total Insecticide Costs	$82.54	$44.30
Total Insect Control Costs	$100.39	$84.96
Yield (lbs. lint)	833	870
Dollar Return	$440.89	$480.75

Source: [159]

Several other studies have been performed, comparing net returns from areas planted to Bt varieties to those planted to conventional varieties. The results of these studies are presented in Table 3.8. The average increase in net returns in Bt acreage from these studies is $38.18, taking into account the technology fees and increased seed costs for Bt variety seed. The average technology fee for Bt cotton was approximately $32 per acre in 1998.

In a 1997 USDA survey of cotton producers, no yield difference was found for growers using Bt cotton varieties compared to other growers who purchased seed. Fewer insecticide treatments were used on Bt acreage in the Southeast, but the same number of treatments were made on Bt acreage in the Delta region, where additional application were made for pests the Bt varieties don't control. Total seed and pest control costs per acre were significantly higher on Bt acreage, attributed to the technology fee on Bt seed [158].

The USDA analysis of the survey data does not take into account any confounding factors which may have influenced the observed differences between Bt cotton users and nonusers. The results are a difference in means, which may be driven by factors unrelated to the adoption of transgenic varieties. For instance, the number of insecticide applications on non-Bt target pests in the Delta region is significantly higher on Bt acreage than on non-Bt acreage. However, some production areas included in this region were undergoing boll weevil eradication, and receiving high numbers of treatments of malathion to control the weevil. In Mississippi in 1997, an average of 8.5 sprays of malathion were made to cotton acreage [10]. Some believe that growers in the boll weevil eradication zones are adopting Bt varieties at a higher rate than other growers in order to achieve control of bollworm/budworm in the face of treatments that destroy their natural predators [156]. Therefore, the difference in number of treatments may be biased due to the unequal number of Bt growers in boll weevil eradication zones. Further analysis of the USDA survey data is necessary to isolate the effects of adoption of transgenic varieties before conclusions can be drawn.

The impact of adoption of the Bt cotton varieties varies depending on pest pressure in a region as well as the particular conditions and management of each grower. Without detailed data on the variability of Bt variety performance, it is necessary to generalize. Based on the survey 1998 grower survey, a yield increase of 37 lbs. per acre [159] translates to 85 million pounds, or 177,000 bales increase in cotton production. If growers are able to reduce the number of insecticide treatments by 2.3 treatments per acre, a reduction in the total number of insecticide treatments in cotton of 5.3 million treatments would be realized. Assuming growers across the cotton belt who adopt Bt varieties experience a $40 per acre advantage in net returns, the total net benefit of adoption of these varieties on US cotton producers was $92 million in 1998. (See Table 3.9.)

Table 3.8. Summary of Studies Comparing Net Returns of Bt and Conventional Varieties

Study	Crop Year	Region	Change in Net Return ($/acre)
Allen, et al. [176]	1998	AR	-11.18
Bryant, et al. 1997 [177]	1996	AR	79.51
Bryant, et al. 1998 [178]	1997	AR	-62.89
Carlson, et al. [157]	1996	NC, SC	53.21
	1996	GA, AL	81.53
Gibson, et al. [179]	1995	MS	94.83
	1996	MS	16.22
Mullins, et al. [159]	1998	AL, AR, GA, LA, MS, NC, SC, TN, VA	39.86
ReJesus, et al. [180]	1996	SC	104.92
	1997	SC	-81.68
Stark [181]	1996	GA	72.80
Wier, et al. [182]	1995	MS	82.50
	1996	MS	24.71
	1997	MS	53.73
	1995-97	AL, GA, FL	54.53
	1995-97	MS, AR, LA	35.53
	1996-97	East TX	11.02
AVERAGE			**$38.19**

Table 3.9. Impact of Adoption of Bt Cotton Varieties in the US in 1998

Acres in Bt Cotton	2,300,000
Costs of Bt Cotton	$74,000,000
Total Benefit	$166,000,000
TOTAL NET BENEFIT	**$92,678,000**

3.J. Summary

The adoption of transgenic cotton varieties containing an insecticidal protein gene from *Bacillus thuringiensis* has provided growers with an additional tool to control three of the most damaging cotton insect pests. Seventeen percent of the total US cotton acreage was planted to Bt cotton varieties in 1998. The impact that this technology has had on cotton production includes reduction in the number of insecticide treatments by a total of 5.3 million less treatments. Yield increases resulting from reduced crop damage total 85 million pounds in increased annual production. The overall net benefit to cotton producers has been an increase in $92 million.

4. Potatoes

4.A. U.S. Potato Production

Potatoes are grown on 1.3 million acres in the U.S. Over 45 billion pounds of potatoes are produced in the U.S. annually [19]. The national value from production of potatoes is approximately $2.6 billion per year or about $2000 per acre. Fifty-five percent of annual U.S. production of potatoes is produced in the Pacific Northwest states of Idaho, Washington and Oregon. Other major potato producing states include Maine, Michigan, Minnesota, Wisconsin, New York, Pennsylvania, North Dakota and Colorado.

Potatoes are annuals produced from certified potato seed pieces taken from the previous year's crop. Potatoes and seed potatoes are produced in the same manner, except that seed potatoes receive more intensive pest management to ensure disease-free planting stock [99].

4.B. Insect Pests of Potatoes

The significance of various insects to potato production differs from region to region. Colorado Potato Beetle is more of a problem in the East than in the Northwest U.S. Potato tuberworms are a problem in the South and in California. Four different flea beetle species infest different regions. Several different aphid species infest potato-production regions. Aster and potato leafhoppers migrate from the South every year to infest potato fields in North Dakota, Wisconsin and Minnesota. These insect species vary in the type of damage they cause to potatoes. Colorado potato beetles and leafhoppers consume plant foliage, that leads to reduced photosynthesis and yield reductions. Flea beetles also consume foliage, but also may damage the underground tubers directly. Aphids suck sap out of foliage. Aphid feeding can reduce potato yields directly through the feeding damage to the foliage, and also indirectly by the transmission of viruses that infect the underground tubers. Wireworms are a problem in many potato growing regions in fields rotated from sod or pasture.

Several factors often contribute to spider mite infestations in potato fields, including proximity of alternate hosts (i.e., corn), dust on surfaces and the use of insecticides for control of other pests. Mites can be held in check by reliance on natural enemies.

The focus of the following discussion will be on the Colorado Potato Beetle and aphids – the species currently affected by genetically engineered potato plants.

4.C. The Colorado Potato Beetle

The Colorado potato beetle (CPB) is the major defoliating insect pest of potatoes in the U.S. It is thought that the Colorado potato beetle originated in Mexico and gradually moved north. Prior to the introduction of the potato in the Midwestern U.S., the insect survived on wild host plants, mainly nightshade and buffalobur. It was well distributed throughout Colorado and as far east as Iowa and Nebraska before potatoes were grown there. By the 1880's it had become established throughout most potato production areas of the U.S. [92].

If uncontrolled, the Colorado potato beetle can defoliate completely all potato plants in a field by mid-season.

Colorado potato beetles overwinter as adults in their field of origin, in uncultivated areas adjacent to the field and in wooded areas away from it. The adult Colorado potato beetle spends the winter buried four to ten inches deep in the soil. A study in the Northeastern U.S. showed that 95% of the adult beetles colonizing a potato field in the spring originated in that same field. Female beetles almost always are inseminated before overwintering, and, as a result, need not mate before dispersal in the spring [100]. Although spring beetles do not need to mate, preliminary observations demonstrated that newly emerged beetles will mate if given the opportunity [100]. Within a few days of colonizing a field, the beetles feed and begin to deposit egg masses composed of 25-50 eggs. Each female can produce about 450 eggs. A single larva consumes about four square inches of foliage before dropping to the ground to pupate. The next generation of adults emerge from the pupae in the soil and begin to lay eggs. The CPB can go through three complete generations per year in some potato growing areas [92].

In fields where potatoes were grown in the previous year, overwintering adults emerge in close proximity and colonize fields by walking from adjacent areas. If the field has been rotated to another crop, the adult beetles need one to two weeks to regenerate their flight muscles. Thus, CPB infestations in potato fields that have been rotated with another crop can be delayed by several weeks [92].

If beetles emerge in the spring in a habitat containing host plants such as potatoes, they rarely will fly; instead, they immediately will feed. If starved, beetles first will walk to find hosts, then resort to flight. The flight may continue for two weeks and result in movement of several miles [100]. The adult beetles can go without feeding for a month.

Most potato growers use crop rotation in their potato production system. However, because of the small size of most Eastern potato farms and their close proximity to one another, the distance between the rotated fields is not great.

Few insects have shown the potential to develop resistance to as broad a range of insecticides as the Colorado potato beetle has. In one locality or another, it has developed resistance to the arsenicals, organochlorines, organophosphates, carbamates and synthetic pyrethroids. The beetle has a great capacity to tolerate exposure to insecticides because of its natural biochemical ability to detoxify and isolate toxins within its body away from physiologically active sites. This ability is related to its natural survival on wild plant hosts that contain high levels of toxins such as alkaloids [92].

The Colorado potato beetle resulted in the first large-scale use of insecticides (Paris Green, 1866) in an agricultural crop. The CPB populations built up and spread rapidly to the East, reaching Iowa in 1861 and reaching the Atlantic Ocean in 1874 [102]. In its first several years as an insect pest of potatoes, CPB appears to have been particularly devastating: Yields were reduced, prices increased and many farmers abandoned the crop [102]. Hand picking was a widely-practiced means of control during the early years. Calcium arsenate was used widely against the CPB before the advent of DDT. The arrival of DDT was fortunate because of the growing awareness of problems of residual arsenic in the soil and on potato tubers [102]. In the years since the failure of DDT, Eastern potato growers have found it necessary to change insecticides every few years as the CPB developed resistance to every insecticide used extensively against it [102].

Propane burners have been tested and used to control the Colorado potato beetle in the East. Propane burners are arranged to straddle the potato row and direct the flame at the plants. This means of beetle control can provide up to 85% control.

Plastic lined trenches have been used to prevent Colorado potato beetles from infesting border areas of potato fields. Beetles fall into and are trapped in the trench. This practice was used on a number of Eastern potato farms in the mid-1990's with some success.

Only a few natural enemies of the Colorado potato beetle are at all useful in biological control of this pest.

The fungus *Beauvaria bassiana* is capable of causing high levels of mortality in CPB populations. However, the fungicides that commonly are used to control blights also kill the fungus. Predatory stink bugs are voracious and can kill a large number of Colorado potato beetle larvae in a short time. However, they are rarely present in numbers great enough to be of much practical value [92]. Constraints associated with biological control of the Colorado potato beetle include: 1) the inability of natural enemies to control high populations of the insect; 2) the timing of life cycles of natural enemies with the potato growth stage when the crop needs protection; 3) the cost of raising and releasing large numbers of insect natural enemies; and 4) insufficient knowledge of which natural enemies are most effective [92].

4.D. Aphids

Most aphids overwinter as eggs on woody plants or trees. If conditions are favorable for aphid development, a single tree potentially can produce enough winged aphids to initiate economic infestations on at least 500 acres of potatoes [98]. In spring, wingless aphids, called stem mothers, hatch. They and all their descendants of the spring and summer are females and reproduce without mating, giving birth to live young. Winged spring migrants are produced and leave the host plant in search of suitable summer hosts – such as potatoes [93]. Spring migrants are capable of traveling long distances. Green peach aphids have been known to travel a thousand miles and have been found in the atmosphere at altitudes of up to 10,000 feet. At the height of the flight, 2.5 million aphids can blanket an acre of potatoes [95].

Winged aphids alight at random since they cannot distinguish a host from a non-host plant from a distance. To find a suitable host, winged aphids feed for short periods on plants on which they land. Once an acceptable host plant is found, the spring migrants settle down and reproduce. The summer reproductive aphid population is wingless. As the day length shortens, fall migrants are produced, both males and females. They return to a winter host plant on which fertilized overwintering eggs are laid [93].

Green peach aphid eggs are produced by sexual females in the fall, but otherwise the cycle is continued with females giving birth to females for 10 to 25 generation during the growing season. Each aphid is capable of producing 30 to 80 nymphs over a period of 10 to 20 days.

When aphid populations in potato crops reach the accelerated growth phase of the seasonal cycle, natural enemies cannot be expected to reduce the populations below economic levels [98].

The potato leaf roll virus (PLRV) is transmitted by aphids. After ingestion of PLRV infected plant sap, virus particles pass through the aphid's gut wall and into the bloodstream. From there, the virus enters the salivary glands, and the aphid can then transmit it to another plant while feeding. Once PLRV is acquired, an individual aphid retains the virus throughout its life [93].

The virus moves in the plant from one cell to another and multiplies in most cells into which it moves. The virus moves rapidly through growing regions and other regions of food utilization in the plant, such as tubers.

PLRV infection symptoms include leaf rolling, stunted plants, and discoloration of leaves, that become stiff, dry and leathery. PLRV infections reduce potato plant vigor and result in high yield losses [104].

The virus is spread in enlarging concentric circle areas around the primary inoculum source as the aphids move from plant to plant. These expanding infestation sites will coalesce and may engulf entire fields within a few weeks if the aphid populations are not controlled [101].

Potato leaf roll viruses invade developing tubers. The infected tubers develop net necrosis or stem end browning. Net necrosis may not be evident at harvest, but symptoms can develop during storage [94]. Potatoes from severely infected fields usually are rejected by processors. Losses in marketable yield have been as high as 50-80% [94].

The Russet Burbank potato variety is the dominant variety in the Northwest. The Russet Burbank is susceptible to potato leaf roll virus and the associated tuber net necrosis. The disease can limit production because the discolored tubers are not suitable for processing or table stock. The green peach aphid is the only important vector of the virus in the West and, because of this, is the key insect pest of Russet Burbank potato crops [98].

Incidence of PLRV infection routinely approaches 100% in potato crops in the Northwest when insecticides are not used [101].

4.E. <u>Insecticide Use</u>

A large percentage of U.S. potato acreage has been treated with insecticides since the 1800's. The Colorado Potato Beetle has been the major focus of annual insecticide applications in eastern areas since the 1880's. The CPB did not become established finally in the Northwest until 1915. Flea beetles, wireworms and aphids became annual control problems for the majority of Northwest potato acreage in the early 1900's.

Many different insecticides have been used for a time in potato production and have been lost through either lack of effectiveness because of pest resistance or have been banned by regulatory agencies. Organochlorine insecticides, such as DDT, Aldrin and Dieldrin, became ineffective for certain pests (such as CPB and aphids) while remaining effective in control of soil insect pests, such as cutworms and wireworms. Their potato registrations were canceled through regulatory actions in the 1970's.

A major chemical breakthrough came in 1975 when aldicarb began to be applied to potatoes. Aldicarb granules incorporated into the soil at planting provided good control for aphids and CPB for the first 90 days of the season [107]. Aldicarb at planting was a popular practice followed by foliar sprays with methamidophos, endosulfan and pyrethroids.

When aldicarb is applied in moist soil, the active ingredient is absorbed in soil water and the pesticide is absorbed rapidly by the germinating seedlings or by established roots.

The toxicant moves upward through the vascular system to all plant parts by systemic action. Pests feeding on leaves or sap are killed by consuming low concentrations of the pesticide in the plant tissue. The persistence of aldicarb's pesticidal activity is estimated at 10 weeks in potato plants [108].

Aldicarb was one of the first agricultural chemicals detected in groundwater. Groundwater detections of aldicarb led to its ban on Long Island in 1980, followed by significant restrictions on its use in other states, such as Wisconsin.

In 1986, aldicarb was prohibited for use in the rest of New York State. In April 1990, Rhone Poulenc voluntarily agreed to halt sales of aldicarb for use in potatoes. This action was in response to test results showing abnormally high residue levels that were found in a small number of potatoes. Aldicarb's use on potatoes was approved for reinstatement by EPA in September 1995, following the development of application equipment that minimized the chance for excessive residues. However, the reintroduction only applies to the states of Idaho, Oregon, Washington, Montana, Nevada, Utah and Nebraska. While the use of aldicarb was suspended, Eastern growers substituted increased foliar applications of methamidophos, cryolite, azinphos methyl and carbofuran. In addition, East Coast growers began using foliar applications of Bt for Colorado potato beetle control. In the Northwest, potato growers responded with the use of more foliar applications of methamidophos for aphid control and switched to the use of phorate at planting time.

The temporary suspension of the use of aldicarb for Washington state potato growers (1988-1993) cost growers and potato processors more than $36 million annually due to the greater incidence of net necrosis [99].

Bacillus thuringiensis var. *tenebrionis* produces a crystal protein (Cry IIIA) that is insecticidal to CPB [103]. When susceptible larvae feed on potato foliage treated with Bt, an endotoxin specific to CPB is released in the gut. This endotoxin inhibits feeding and ultimately causes death [97]. Bt sprays can be used effectively to maintain CPB populations below economic injury levels. However, the Bt sprays have several shortcomings: they are only effective against early CPB instars; they have little residual activity; and they have stringent requirements for precise application timing and other conditions for optimum activity [100].

Prior to the 1995 season, imidacloprid was registered for potatoes. Research indicated that imidacloprid provided a high degree of CPB control compared with other alternatives. Imidacloprid is applied in furrow when the potato seed is planted and is taken up through the plant, persists in the plant and controls insects that feed on the plant. Following the introduction of imidacloprid in 1995, Eastern potato growers stopped using all of the cultural methods of beetle control (burners, trenches), except for crop rotation. Recent pesticide use surveys for Eastern states show that imidacloprid is used on a high percentage of the acres (> 80%) and displaced the use of Bt and cryolite while reducing the use of other foliar insecticides such as methamidophos and azinphos methyl. The cost of an imidacloprid application at planting is $60 per acre [96]. In the Northwest, the reintroduction of aldicarb led to reductions in the foliar applications of methamidophos. Table 4.1 displays current potato insecticide use data for US potatoes.

As can be seen, US potato growers apply approximately 2.5 million pounds of insecticides annually. Most insecticide usage in US potato production is directed at Colorado potato beetles and aphids.

With the exception of propargite (used for mite control), all of the insecticides used commonly in the Pacific Northwest are used primarily to control aphids and and/or Colorado Potato Beetle [110]. With the exception of carbaryl, diazinon, dimethoate and methyl parathion, all of the insecticides used commonly in Eastern potato fields are directed primarily at CPB and aphids [111].

In the Northeastern U.S., one well timed spray with methamidophos in July is usually sufficient for aphid control.

Several of the insecticides used in potato production can be applied either to the soil or as foliar applications (imidacloprid, carbofuran) while others are applied exclusively to the soil (aldicarb, phorate) or exclusively to foliage (methamidophos, esfenvalerate, permethrin).

Systemic insecticides (such as aldicarb, phorate, imidacloprid) applied to the soil control first generation beetles but may no longer be effective if the second generation moves in from an adjoining field.

Because they do not kill aphids quickly enough to prevent transmission of PLRV, neither carbofuran nor methamidophos limits introduction of PLRV into potato fields. These insecticides control PLRV, not by preventing introduction of PLRV by aphids, but by limiting secondary spread [101].

Currently in the Eastern U.S. all field populations of the Colorado potato beetle are still susceptible to Bt and imidacloprid. Resistance to other insecticides (such as azinphos methyl) is highly variable between regions and even between fields [100]. In the West, CPB has developed little resistance.

Imidacloprid has dramatically reduced populations of CPB in Eastern states. The reduction in CPB populations has been estimated to be as high as 99.9% in some locations [100]. Thus, CPB populations throughout the Midwestern and Eastern potato growing regions of the U.S. have been decimated [100]. Yield losses to Colorado potato beetle are minimal to nonexistent [96].

Growers can expect to achieve practical season-long control of CPB with soil applications of imidacloprid at planting or one to three foliar applications.

4.F. Bt Potato

In the 1980's scientists transformed potato plants through insertion of a gene from the bacteria *Bacillus thuringiensis*. The transformed potato plants express the Bt toxin throughout the plant. The Colorado Potato Beetle ingests the toxin in trying to feed on the plant. The endotoxin is activated in the CPB's gut by enzymes. The toxin binds to membranes in the gut, and pores are formed. Cells in the gut rupture and the CPB larvae die.

The Cry III (A) delta endotoxin produced in potatoes is identical to that found in nature and in commercial Bt formulations. However, these potatoes produce the Cry III (A) delta endotoxin throughout the plant for the length of the growing season at a level sufficient to control all life stages of the CPB. In contrast, the application of foliar Bt must be frequent and carefully timed to adequately protect the crop [113].

Field experiments conducted at more than 30 locations throughout the U.S. potato growing region since 1991 demonstrated that Bt potatoes are protected season long from all CPB lifestages. Growers who use *B. thuringiensis* plant-pesticides do not require chemical insecticide applications to control CPB. The Long Island, New York potato production area has CPB populations which are highly resistant to most chemical insecticides. *B. thuringiensis* plant-pesticides produced by potatoes were tested on Long Island and provided excellent, season long control of all stages of CPB and produced high yields without relying on other chemicals for control of CPB [113].

Monsanto and its seed subsidiary, NatureMark, have commercialized BT potatoes as New Leaf® potatoes.

New Leaf® potatoes are so effective, no CPB larvae have ever been found to survive. Growers are instructed that they never should see CPB larvae on New Leaf® foliage.

The transformed potato plants have agronomic and tuber characteristics consistent with standard Russet Burbank plants [103]. In taste tests, the transformed potatoes compared favorably with control Russet Burbank potatoes [103].

New Leaf® potatoes are advertised as smoother than unimproved Russet Burbank. In addition, the New Leaf® potatoes are reported to bulk earlier and to provide a high percentage of US#1's.

Yield data for 1996 and 1997 commercial fields (101 fields) indicated that fields of New Leaf® and unimproved Russet Burbank cultivars produced approximately identical yields.

The New Leaf® potato technology fee was about $30 per acre in 1998. Growers who planted the seed include those with a history of light infestations of pests other than CPB. Avoiding an at-plant insecticide application cost of $60 per acre represented a savings of $30 per acre. If only one foliar application was needed during the year for aphids ($20/A), the grower could save $10 per acre. Some of the growers planting New Leaf® have been interested in supporting and trying the technology while others selected the New Leaf® potato seed for other agronomic considerations. Most growers did not change their insect control practices and still used the at planting systemic insecticide.

Monsanto data showed that in 1997 growers using New Leaf® potatoes, on average, made one less insecticide application than conventional growers (2 vs.3).

Bt potatoes were planted in approximately 4% of US acreage in 1998 [114]. Generally, the small percentage is reflective of the need for potato growers to control other insect pests in addition to the Colorado Potato Beetle. As mentioned above, an at-planting application of a systemic insecticide (such as aldicarb or imidacloprid) provides residual control of CPB, aphids and other foliar feeders. The Bt potato controls the CPB exclusively. Thus, since most growers would need to apply the insecticides anyway to control other insect pests, it does not pay for them to incur the cost of the Bt potato seed to control a pest (CPB) that would be controlled as well with the insecticide.

4.G. Virus Resistant Potato

Russet Burbank potatoes have been transformed with plant expression vectors containing a potato leaf roll virus (PLRV) protein gene.

The protein gene was mated into *Agrobacterium tumefaciens*. Russet Burbank potatoes were transformed with *agrobacterium* containing the double gene constructs [101].

Potato Leaf Roll Virus Resistance gene (also known as orf1/orf2 gene) is the active ingredient in New Leaf Plus® potatoes. The transformed potato contains .03% Potato Leaf Roll Virus Resistance gene [112]. The New Leaf Plus potato also contains the Bt toxin gene. Induction of resistance to PLRV infection by the orf1/orf2 gene is not clearly understood at present. The orf1/orf2 gene does, however, induce virus resistance by a non-toxic mode of action.

The Russet Burbank potato was transformed through insertion of the PLRV replicase protein gene. The presence of the protein gene in the plant interferes with the viral replication process.

When concern for PLRV is eliminated, it is estimated that potato growers will be able to significantly reduce the need for insecticides. In 1998, New Leaf Plus® potatoes were grown on eight farms in the Columbia Basin and three farms in Idaho. On the 350 acres of New Leaf Plus® grown in the Columbia Basin in 1998, growers realized a savings of $97 per acre in insecticide and application costs. (Miticide applications were still necessary.) The technology fee for New Leaf Plus® represented a cost of approximately $46 per acre, resulting in a net gain of $51 per acre.

One key criterion for treating high populations of wingless aphids in New Leaf Plus ® potatoes is whether they have reached a point of crowding such that immature aphids have started to develop wings. Such populations should be treated to prevent generating large numbers of winged adults that may contaminate other fields.

New Leaf Plus® potatoes do not kill aphids, but are protected from the virus that aphids transmit. As a result, aphids can be tolerated at much higher numbers. It is estimated that aphids in excess of 10 aphids per leaf (on average) can exist on potatoes without causing feeding damage.

In Idaho, aphid populations remained low on two of the three New Leaf Plus® fields. In one field, however, aphid populations reached the treatment threshold, and an insecticide application was made. In Idaho, the conventional insecticide program cost $50 per acre while the New Leaf Plus® insecticide program cost $9 per acre. The technology fee for New Leaf Plus® in Idaho was, approximately, $40 per acre in 1998, equaling the chemical cost savings on these fields. Although New Leaf Plus® would be expected to eliminate most insecticides for foliar pests in Idaho, many growers would still apply systemic insecticides, such as phorate for control of wireworms.

In other parts of the country (such as Wisconsin, there would still be a need to apply insecticides to control migratory leafhoppers.

4.H. Summary

The introduction of genetically transformed potato plants has not had a major impact on production costs, insecticide use or yields. In 1998, only 4% of U.S. potato acreage was planted with Bt potatoes, meaning that growers did not have to apply insecticides to control the Colorado Potato Beetle. However, since these growers had to apply insecticides for other insect pests during the season, the reduction in insecticide costs and insecticide application amounts was minor. The yields of the transformed and unimproved potatoes were approximately the same.

With the introduction of potato plants that resist viral infections, as well as providing control of the Colorado Potato Beetle, the expectation is that there will be a significant decrease in insecticide use amounts. EPA officials have publicly stated their expectation that thousands of pounds of insecticides now used to kill aphids would no longer be used if the virus resistant potatoes were to be planted on a significant amount of potato acreage [115].

Table 4.1 Insecticide Use: US Potato Production

Active Ingredient	Acres Treated		Lbs AI	
	#(000)	**%**	**per Acre**	**Total (000)**
Aldicarb	102	8	2.79	284
Azinphos -methyl	100	8	0.52	52
Carbaryl	40	3	1.06	42
Carbofuran	248	20	0.93	230
Diazinon	12	1	1.53	18
Dimethoate	344	28	0.74	254
Disulfoton	25	2	2.44	61
Endosulfan	196	16	0.96	188
Esfenvalerate	141	11	0.04	6
Ethoprop	26	2	4.86	126
Imidacloprid	275	22	0.16	44
Methamidophos	370	30	1.20	445
Methyl Parathion	18	1	1.42	25
Oxamyl	6	1	0.82	4
Permethrin	88	7	0.12	10
Phorate	242	20	2.66	644
Propargite	51	4	1.92	98
				2531

Derived from USDA NASS data for 1996-98 [10]. Weighted averages computed from state data for regions: East, North Central and Northwest. Regional data weighted to national level based on acreage. Total U.S. acreage estimated at 1.3 million.

5. Summary and Conclusions

The insect pests controlled by genetically-engineered crops have been long term problems for U.S. growers. The European corn borer, Colorado potato beetle, tobacco budworm, cotton bollworm and pink bollworm have been the subjects of enormous, publicly-funded research programs focused on their control. Attempts to control these insect pests with biological methods have not proven successful despite many decades of research. Many potential chemical and non-chemical methods of controlling these pests still are being researched.

Biotechnology methods have produced corn, potato and cotton varieties that contain genes for a protein that effectively controls these highly injurious pests when they attempt to feed on the plants. The genetically-engineered plants are highly effective in reducing populations of these insects.

An accurate assessment of the contribution of a new pest control technology would require a decade or more of actual field usage. Environmental and economic conditions that face U.S. farmers vary widely from year to year, and only in a long term assessment do the underlying trends become obvious. This report’s assessment of the benefits of the introduction of insect control products produced using modern biotechnology methods relies on analysis of the first two to three years of field usage.

A key feature of the biotechnology crops is that the control technique is carried in the seed that is planted at the beginning of the season. A farmer must incur the costs of the technology before knowing the levels of pest infestation during the growing year or the price that will be received for the crop at the end of the year. Thus, it is to be expected that wide variations in actual net returns will occur.

This highly variable situation is perfectly illustrated in the case of Bt corn. In 1997, corn growers gained $72 million in income from the planting of Bt corn. However, in 1998, with three times more acreage planted to Bt corn, growers lost $26 million by planting Bt corn because pest infestation levels and the price of corn dropped to well below average. An analysis of the historical pest infestation data suggests that three non-paying years for Bt corn can be expected every decade. These average values mask the fact that not all farmers incur the same result during the same year. There were corn farmers who faced high pest pressure during 1998 and derived positive net benefits from planting Bt corn.

Although the increased corn yield in 1998 was not enough to pay for the Bt corn technology premium, a significant increase in corn production did occur as a result of the technology. An additional 4.2 bushels per acre were produced on 14.4 million acres, resulting in an additional 60 million bushels of corn being produced in 1998 as a result of the planting of Bt corn. If Bt corn had not been planted in 1998, those 60 million bushels (4 billion pounds) would have been lost because of the feeding of the European corn borer. If Bt corn had not been planted in 1998, the nation's farmers would have grown the equivalent of 450,000 acres of corn that would have been destroyed by the corn borer.

Because farmers have been reluctant to scout for the corn borer, and because the timing of chemical sprays is difficult, insecticides traditionally have not been used to control the European corn borer. Thus, although 18% of the nation's corn acreage was planted to Bt corn in 1998, a reduction in insecticide use occurred on only 2.5% of the corn acreage. On the 80 million acres of corn that were grown in 1998, the 2.5 % reduction in acres treated means that 2 million fewer acre treatments were made with insecticides on corn acreage in 1998 because of the planting of Bt corn.

A somewhat different situation occurred in cotton in 1998. Bt cotton was planted on 17% of the nation's cotton acreage in 1998, primarily in the Southeast, Mid-South and Arizona. This acreage would have received approximately 5 million more acre treatments with insecticides had Bt cotton not been planted. Cotton growers saved the cost of the insecticides and produced an extra 85 million pounds of cotton because the Bt cotton plants were more effective than the insecticides in controlling the target insect pests. In the aggregate, cotton farmers gained $92 million in net income as a result of planting Bt cotton in 1998.

For potatoes, the impacts of the introduction of cultivars that resist the Colorado potato beetle have been minor. Potato growers have effective insecticides to control the Colorado potato beetle and other insect pests, including aphids. As a result, growers have had little incentive to plant the genetically-engineered crops as they need to apply the insecticide anyway to control the other pests. However, the recent introduction of genetically-altered potato cultivars that control the Colorado potato beetle and resist virus infections caused by aphids has the potential to significantly reduce insecticide use in potatoes.

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