Plant Resistance to Insects in Integrated Pest Management

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ABSTRACT
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Resistance in plants to insects is usually associated with the relative amount of damage to plants by pests compared with damage on more susceptible crops. Plant resistance mechanisms are nonpreference, antibiosis, and tolerance. Discussions are presented to illustrate the value of plant resistance in an integrated pest management system with nonpreference, antibiosis, or tolerance as the basis of the resistance. Plant resistance is also shown as the primary insect control agent or in an integrated pest management system with insecticides, biocontrol agents, inherited sterility, or cultural control. Regardless of the situation, a resistant cultivar is more desirable than a susceptible cultivar. The use of the resistant cultivar is biologically, ecologically, economically, and socially feasible.

Additional keyword: IPM

The trend in insect control is to decrease the use of conventional insecticides, not only because of the cost, but also to minimize environmental disruption and avoid the development of pesticide resistance. Headley (13) predicted that chemical control would have a major role in pest management in crops until 1992, and then the trend toward nonchemical control methods would increase (Table 1). He also predicted that resistant cultivars would play a major role in controlling pests until 1992 and that the demand for their use would sharply increase after that time. Plant resistance to insects, integrated with other biocontrol strategies, should be one of the principal means of nonchemical control of pests.

Integrated pest management (IPM) is not new; it has been in existence since the mid-1950s and even much earlier, when other terms were used (10,22,42). IPM has been defined (10) as a "pest management system that, in the context of the associated environment and the population dynamics of the pest species, utilizes all suitable techniques and methods in as compatible a manner as possible and maintains pest populations at levels below those causing economic injury." Pedigo (36) suggested that some of the strategies that may be applied to managing insects for a pest management program may be compared with those of constructing a building. Species biology, population sampling, and artificial rearing of the insect are valuable components. As a broader base, bioeconomics and population dynamics are equally important. For the tactics used in population suppression, the individual components of the integrated approach should be used; for overall plant protection, the use of all available components in one package is of utmost importance.

Kendrick (20) stated that the key ingredient of integrated control is information. We must have a knowledge of the various components of managing each pest within the crop system. This technology must be disseminated and adopted for on-farm use before we can realize the effects of the various combinations of control measures. Our challenge today is to provide solutions and to use them efficiently in programs with management consultants to minimize insect losses without sacrificing environmental quality.

A knowledge of pest–crop interactions in the management of insect pests is of paramount importance. The development and use of a particular cultivar is the base from which all management strategies must arise. If the crop cultivar is susceptible, i.e., one that is readily attacked and damaged by the pest, then chemical control is likely to be used. However, if the crop cultivar is resistant, i.e., it is inherently less damaged or less infested than comparison cultivars (31), then the decisions for integrated pest management should consider that fact. Resistant cultivars include the transgenic plants being rapidly developed today.

Value of Plant Resistance

Luginbill (25) reported that the most effective and ideal method of combating insects that attack plants was to grow insect-resistant varieties; he further showed the value of research and development of resistant plants to be about $300 return for each $1 invested. McMillian and Wiseman (27) also estimated that for each $1 invested by USDA from 1950 through 1970 on research on resistance in corn to *Helicoverpa zea* (Boddie), $20 was returned to the grower in the form of an increase in corn yield. Before 1951, the production of sweet corn was unprofitable in the southeast, even with the use of pesticides. However, in 1951, Ioana sweet corn was released to growers with low to intermediate levels of resistance to corn earworm. This single release allowed growers to produce sweet

Table 1. Predictive components of future pest control[a]

Technique	Probable use to 1992	Trend
Chemical methods		
Insecticides	Major	Declining
Mechanical methods	Minor	Declining
Biological methods		
Parasites, predators	Minor	No change
Bacteria	Minor	Increasing
Viruses	Not significant	Increasing
Pheromones	Not significant	No change
Resistant varieties	Major	Increasing
Pest genetics	Minor	Declining
Cultural methods		
Crop rotation	Minor	Declining
Trap crops	Minor	No change

[a] Modified from Headley (13).

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corn with pesticides. Today, higher levels of resistance in sweet corn are available to growers, as evidenced by the fact that Ioana is used in many studies as a susceptible check. The Purdue–USDA small grains improvement program has estimated a $3.4 billion increase in farm income attributable to improved cultivars of wheat with resistance to the Hessian fly, *Mayetiola destructor* (Say) (38). The annual return exceeded $4.6 million per scientific year invested, calculated over a 64-yr period of the program. Buntin and Raymer (2) reported the economic benefit of using resistant wheat cultivars in Georgia to control the Hessian fly averaged $104 per hectare.

Classifications of Resistance

Some of the more conventional classifications of resistance include those reported by Painter (31,32), Horber (15), Gallun and Khush (9), and Vanderplank (46,47). They include the following:

Immunity. An immune plant or cultivar is one that a specific insect will not damage or use under any known condition. An immune plant is a nonhost.

High resistance. A cultivar with high resistance possesses attributes that result in small or minor damage by a specific insect under a given set of conditions.

Moderate resistance. A moderate or intermediate level of resistance results from any one of at least three situations: 1) a mixture of phenotypically high and low resistant plants; 2) plants homozygous for genes that under a given environmental condition produce an intermediate level of injury; and 3) a single clone that is heterozygous for incomplete dominance for high resistance.

Low resistance. A low level of plant resistance indicates attributes possessed by the cultivar that result in less damage or infestation by an insect than the average for the crop.

Susceptibility. A susceptible cultivar is one on which average or more than average damage is inflicted by an insect pest species.

Vertical or specific resistance. Implies that a series of different cultivars of the same crop infested with a series of different insect biotypes of the same species shows a differential interaction. Some cultivars are classed as resistant and others as susceptible when infested with the same insect biotype. Biotype-specific resistance is another term used to describe vertical or specific resistance that is usually controlled by a major gene(s). Vertical resistance is usually less stable than horizontal resistance.

Horizontal or general resistance. Implies that the level of resistance offered by a particular host cultivar is similar against all or several insect biotypes. Horizontal or general resistance is controlled by several genes and is usually considered stable and permanent.

The more specific insect resistance terms discussed hereafter will be those by Painter (31,34). The use of insect-resistant plants is usually associated with reduced crop damage by pests (31). Painter attributed resistance to heritable qualities of the plant. A resistant plant is always resistant to a specific pest species under given environmental conditions; if the environment changes, the level of resistance may or may not change. Mutations in a resistant plant genotype may or may not result in resistance, but its predecessor remains resistant to the pest insect. A pest insect may form new biotypes, whereas the original insect biotype remains susceptible to the resistant plant genotype. Resistance in plants to insects is more stable than the insect pests, as evidenced by the number of biotypes in certain crop–insect relationships, i.e., the Hessian fly. There are about 14 different insect species, out of more than a thousand species that attack domestic crops, that have formed biotypes in seven crop–insect relationships (40).

Mechanisms of Resistance

Painter (34) proposed three distinct mechanisms of resistance: tolerance, nonpreference (antixenosis), and antibiosis. 1) Tolerance to insect damage is a resistance mechanism that allows the plant to grow and reproduce or repair injury despite supporting a density of insects approximately equal to what would be damaging to a susceptible cultivar (31). 2) Nonpreference denotes a group of plant characters and insect responses that lead an insect away from a plant or plant part for oviposition, food, shelter, or a combination of the three. Painter (34) delineated nonpreference into two distinct actions of choice by insects among cultivars: a choice to oviposit, establish, or feed when only one cultivar or plant part is available; and a choice to oviposit, establish, or feed when more than one cultivar is available. Owens (30) further described these two types of nonpreference as relative and absolute. Antixenosis was proposed by Kogan and Ortman (23) as a substitute for nonpreference since it parallels antibiosis. However, most workers in plant resistance to insects continue to use nonpreference since our biennial workshop adopted its continued use. 3) Antibiosis is the mechanism of resistance that produces adverse effects on parameters of the insect life history when a resistant plant is used for food (31). The effects of an insect feeding on a plant with this type of resistance may be death of the neonate (larva or nymph), reduced food consumption that results in a smaller size or lower weight, increased developmental time, low food reserves, reduced weight of pupae, death in the prepupal stage, and/or reduced fecundity.

Resistant cultivars often possess combinations of these resistance mechanisms, especially with regard to nonpreference and antibiosis. With a combination of resistance mechanisms, a cultivar that is nonpreferred does not require the same level of antibiosis or tolerance that a more preferred cultivar must possess to attain the same level of resistance. Thus, different cultivars may possess the same levels of resistance with different mechanisms of resistance.

Our goal is to develop cultivars with multiple mechanisms of reistance, multiple genes for resistance, and more specifically, multiple pest resistance. The biological and genetic bases of the resistance need to be known to successfully incorporate multiple resistance characters into the same cultivar. Sometimes these factors are antagonistic. However, with a sound biological basis and restriction fragment length polymorphism analysis of the plant, gene transfer can possibly be accomplished more easily and more rapidly than classical plant breeding. This may be especially true when more exotic plant material is used. Often, not enough plant material has been screened to find adequate levels of resistance to transfer to more adapted plant materials. In some cases, being able to artificially rear the insect pest can enhance the search for higher levels of resistance. But when high levels of plant resistance have been found and developed into adapted cultivars, their use in the management of the pest can be demonstrated as described below.

Resistance Mechanisms and IPM

As mentioned earlier, knowledge of the insect–plant interactions or mechanisms of resistance is important for the correct use of the resistant cultivar in an integrated pest management system. Insect–plant interactions may occur at several different levels, i.e., between or among different crop species or among different varieties within a species, within a field planted to a resistant variety, and finally at the plant level (48). Interactions also occur between the insect and the mechanisms of resistance (31).

A few specific examples of the success of plant resistance in integrated pest management will be given. Even though there are many examples of successes of plant resistance, failures also occur. Some may say that when an insect biotype develops and overcomes the former resistant cultivar, this a failure. However, the resistant cultivar remains resistant to the original insect population. There also are examples where a resistant cultivar was developed for one insect species and when released was found highly susceptible to another insect species.

The resistant cultivar has traditionally been used in one of two ways: as a primary method of control, and as an adjunct to other control components of IPM. The following will illustrate how each mechanism of resistance can operate as the primary method of controlling insect populations and/or limiting damage.

Resistant cultivar as primary method of control. There are many cases where the use of resistant cultivars is the primary method of suppressing insect densities or reducing damage. Plant resistance was historically sought in areas and for crops where plant resistance was the only possible plant protection method (14); for example, grape rootstocks resistant to *Phylloxera* sp. were first used in 1870 to control this pest in France and save the French wine industry. The resistant rootstocks were used worldwide, resulting in an effective control lasting more than 100 yr (41). Wheats resistant to the Hessian fly and the wheat stem sawfly, *Cephus cinctus* Norton, are present-day examples; the planting of some 8.6 million hectares of corn hybrids resistant to the European corn borer, *Ostrinia nubilalis* (Hübner), is another example (39). The effects of the resistant cultivar on the insect were specific, cumulative, and persistent (33). Adkisson and Dyck (1) stated that reduction in pest numbers achieved through the use of resistant plants is constant, cumulative, and practically without cost to the grower. However, higher cost for seed of the resistant cultivar is expected with the advent of the biotechnology-transformed cultivar.

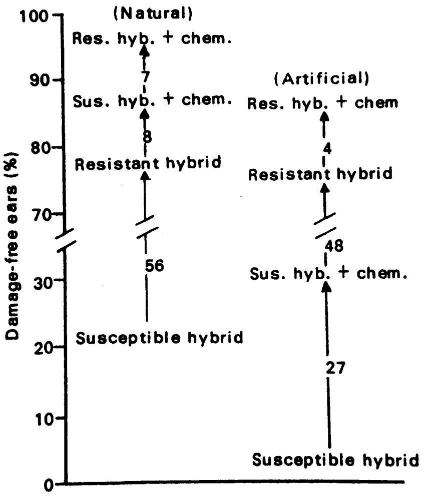

Fig. 1. Percent damage-free ears resulting from combinations of resistant or susceptible sweet corn hybrids with insecticides and natural or artificial infestation of corn earworm (28).

Tolerance. A crop or plant may be tolerant if it can yield well despite infestations that seriously damage susceptible plants (31). Insect populations on the tolerant cultivar are neither reduced nor affected adversely. Interactions between the pest and the resistant cultivar are not considered to occur, since this phenomenon is entirely a plant response. Many corn hybrids that have long, tight husks, more than 10-g silks, and no antibiosis, limit damage by the corn earworm but do not reduce insect numbers (55). Also, we have shown that a sweet corn hybrid, 471-U6 × 81-1, was tolerant to corn earworm damage where the larvae fed in the silk channel and completed its life cycle without inflicting significant damage to the ear (52). The use of the tolerant variety also offers the grower several alternative methods of pest control: 1) pesticides at reduced rates (28,50) (Fig. 1); 2) parasites or predators (43,44) (Fig. 2); 3) cultural control (early plantings); and 4) insect pathogens (8).

Nonpreference. A crop or variety may be nonpreferred when it possesses plant characters that stimulate insect responses that cause it to be used less than another for oviposition, shelter, food, or a combination of the three (31). Two examples illustrate the value of nonpreference resistance in the control of insect populations. Dahms (7) showed in a simple mathematical model (Table 2) the differences in the development of an aphid population over 50 days on a resistant and a susceptible cultivar. Beginning with one aphid on the resistant cultivar and two on the susceptible, at the end of 50 days, 15,502 aphids would have developed on the resistant cultivar compared to 31,004 on the susceptible. In a quite different example, resistance in sorghum to the sorghum midge, *Contarinia sorghicola* (Coquillett), has two nonpreference factors. One is the difference in adult visitation to susceptible and resistant sorghum, and the other is a contact oviposition deterrent within the sorghum spikelet that results in a longer probing time for females depositing eggs and ultimately reduced fecundity (45). Teetes (45) also reported that the economic thresholds levels (ETL) for the resistant sorghum hybrids ranged from 1.0 to 6.0 midges per panicle, whereas on susceptible hybrids the ETL was 0.2 to 1.2 midges per panicle, resulting in a fivefold increase in the ETL for the resistant hybrids over the susceptible.

Antibiosis. Antibiosis is the mechanism of resistance that produces adverse effects on the insect when it uses a resistant plant for food (31). Several examples illustrate the antibiotic effects of the resistant plant. The high antibiotic effects of resistant wheats against the Hessian fly have been the major control component for reducing damaging populations of this pest beginning as early as 1792 (12). Dahms (7) illustrated (Table 3) the differential rate of aphid nymphal development when nymphs matured in 5, 10, and 20 days, and all adults reproduced one per day for 20 days. At the end of 5 days, there were no differences in the aphid population; however, by 25 days, there were 10 times as many aphids on susceptible plants as on intermediate resistant plants. By 50

Table 2. The effect of nonpreference on an insect population with aphids reproducing one per day for 20 days, nymphs maturing in 10 days, no nymphal mortality[a]

Days after first reproduction	Total living aphids with number of vivparous females on plants	
	Nonpreferred cultivar	Preferred cultivar
5	6	12
10	11	22
20	76	152
30	450	900
40	2,620	5,240
50	15,502	31,004

[a] Modified from Dahms (7).

Table 3. The effect of rate of nymphal development on an aphid population starting with one viviparous female, adults reproducing one per day for 20 days, no nymphal mortality[a]

Days after first reproduction	Total living aphids with nymphal development (days)		
	20	10	5
5	6	6	6
25	35	175	1,751
50	585	15,502	1,955,056

[a] Modified from Dahms (7).

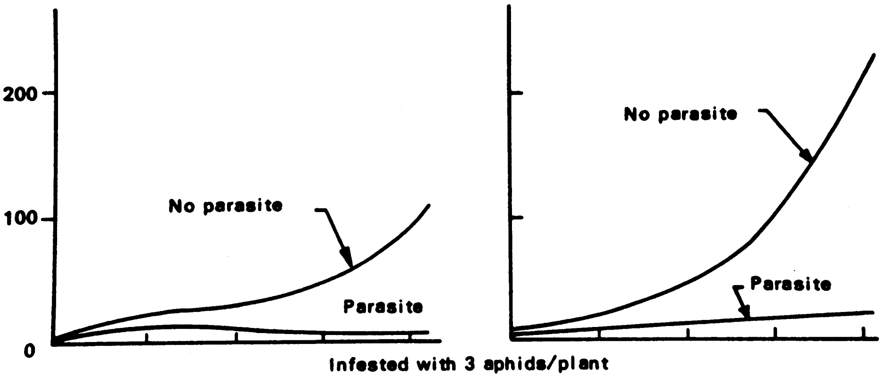

Fig. 2. Increase of greenbugs in the absence and presence of one female parasite caged on greenbug-resistant (Will, left) and susceptible (Rogers, right) barley infested at the rate of three aphids per plant (44).

days, there were more than 125 times as many aphids on susceptible plants as on intermediate plants, and more than 3,300 times more aphids on susceptible than on resistant plants. Mortality of immature stages of insects is one of the most important limiting factors in the increase of insect populations. Table 4 illustrates the effects of 0, 50, and 90% mortality on an insect population over 50 days. There is almost a 15-fold increase at 50 days for 0 vs. 50% mortality, but a more than 100-fold increase at 50 days for 50% vs. 90% mortality, and a more than 1,000-fold increase at 50 days for 0 vs. 90% mortality. At 90% mortality, there was essentially no increase in the insect population. In a more dramatic illustration (Table 5), Dahms (7) showed the population effects of a resistant alfalfa, Lahontan, and a susceptible Chilean alfalfa on the spotted alfalfa aphid, *Therioaphis maculata* (Buckton). Using four factors of antibiosis in a cumulative model, there were more than nine times as many aphids on Chilean as on Lahontan after 5 days; more than 4,800 times as many on Chilean as on Lahontan after 25 days; and almost 14 million times as many on Chilean as on Lahontan after 50 days.

In our studies at Tifton, we found that resistant corn lines reduced fall armyworm, *Spodoptera frugiperda* (J.E. Smith), populations by 50% (54). Also, Wiseman and Isenhour (51) found that resistance in corn silks slowed the growth of corn earworm larvae, extending the life cycle by about 20 days and reducing egg production almost 65% per generation.

Field performance of elite transgenic maize plants expressing an insecticidal or antibiotic protein derived from *Bacillus thuringiensis* killed from 95 to 100% of the European corn borer larvae (24). Also, they found that damage to the leaves by larvae was reduced by more than 50%, and stem tunneling was reduced by as much as 97% of the control. This type of resistance will preclude the use of any other integrated pest management components other than cultural control and the use of classical plant resistance.

Plant resistance and IPM. Resistant cultivars can also be used in combination with other control components of IPM. When the resistant cultivar is developed, it may possess resistance to more than one insect species. Hence, we have pest management of several insect species in one cultivar. Overman (29) reported that several of Dekalb's plant materials had leaf-feeding resistance to several leaf-feeding lepidopterous insect species. The development of resistant cultivars should discourage the use of susceptible ones in an integrated pest management system. Adkisson and Dyck (1) stated that the integrated system is designed to suppress pest numbers below crop-damaging levels, not to replace chemical pesticides. They further stated that a resistant variety provides a foundation on which to build an integrated control system.

Resistant cultivar as component of IPM. When a cultivar has a lower degree of resistance, other control components must be used to achieve pest control levels that permit growers to attain the desired margin of profit. In most cases, the use of a highly resistant crop cultivar eliminates the need for most other control components. But this does not necessarily have to be the practice. For example, with a highly tolerant cultivar, other control tactics are needed to keep the pest insect population in check. In addition, even with highly antibiotic or nonpreferred resistance, other control components should be used to achieve greater overall success in reducing populations of the pest.

Plant resistance and insecticides. In most cases, the use of resistant cultivars is compatible with insecticidal control. For many years, corn, especially sweet corn, could not be grown economically in the southern United States until moderate resistance to corn earworm was introduced into hybrids (26). Ioana sweet corn was cited as the hybrid introduced. Sweet corn could then be produced with insecticide control. Wiseman et al (50) demonstrated the use of a resistant (tolerant) sweet corn hybrid in combination with insecticide to reduce losses from the corn earworm. By use of a resistant cultivar, an insecticide reduction of 7.5 kg/ha was realized, through a reduction in both rate and the number of applications. Another example, the use of sorghum hybrids resistant to greenbugs, *Schizaphis graminum* (Rondani) biotype C, permitted the use of extremely low dosage rates of insecticides (6). Low insecticide rates also preserved natural biological control agents that prevented resurgence of the greenbugs. Conversely, insecticide treatments induced resurgence of the brown planthopper, *Nilaparvata lugens* (Stål), on resistant varieties (37). In this case, the compatibility of the resistant cultivar and insecticide application is lacking. However, this instance with the brown planthopper and the application of insecticide may be an isolated case and may not apply to all insecticides, the planthopper, or the use of resistant varieties of rice.

Plant resistance and biocontrol agents. Plant resistance and biocontrol agents should be compatible in reducing populations of the pest. However, Campbell and Duffey (3) showed that the resistant tomato with tomatine adversely affected the parasite, *Hyposoter exiguae* (Viereck), of the tomato fruitworm. Kennedy et al (21) reported that 2-Tridecanone/glandular trichome-mediated resistance in a wild tomato adversely affected several species of parasitoids and predators of the tomato fruitworm. Rates of parasitism or predation, and parasitoid survival were lower on PI134417 foliage than on susceptible foliage. Also, a high level of resistance in soybeans was found to be detrimental to the parasite *Microplitis demolitor* Wilkinson (56). But Isenhour and Wiseman (16) found no change in pupation, weight of pupae, and time to adult eclosion of the parasitoid *Campoletis sonorensis* (Cameron) when the host fall armyworm larvae fed on resistant corn foliage. In fact, they found that the combined effects of the parasite and plant resistance were additive and beneficial in reducing consumption of foliage, weight of larvae and pupae, and number of fall armyworms produced. Pair et al (35) found that fewer fall armyworms established on Pioneer X304C and Antigua 2D-118, but rates of parasitism were higher on these two resistant lines than on susceptible lines. In another study, Isenhour and Wiseman (17) found that combining the parasite and resistance was additive in reducing the growth of the fall armyworm. The life cycle of the parasite was prolonged but not more than that of the larvae that were fed on the resistant plant alone. Thus, the surviving larvae on a resistant cultivar would have an increase in their life cycle that should coincide with the similar increase in the life cycle of the parasites emerging from fall armyworms that fed on the same resistant cultivar. In some cases where adverse interactions

Table 4. The effect of nymphal mortality on an aphid population starting with one viviparous female, nymphs maturing in 10 days, adults reproducing one per day for 20 days[a]

Days after first reproduction	Total living population with nymphal mortality (%) 0	10	90
5	6	5	2
25	175	141	4
50	15,502	10,431	9

[a] Modified from Dahms (7).

Table 5. Cumulative effect of four antibiosis factors on an aphid population on resistant (R) and susceptible (S) cultivars[a]

Days after first reproduction	Total living population with antibiosis factors: Lahontan (R)[b]	Chilean (S)[c]
5	2	19
25	12	58,489
50	87	1,216,252,841

[a] Modified from Dahms (7).

[b] Reproduced at 2.5 per day for 13 days; nymphs mature in 9 days.

[c] Reproduced at 4 per day for 13 days; nymphs mature in 6 days.

of the resistant plant and the biocontrol agent occur, we may be sacrificing the resistant plant to promote biological control. Many of the IRRI rices had such high levels of resistance that biocontrol agents were finding it difficult to increase. But is that all bad? We've limited insect losses. If the pest insect can readily adjust, then we can assume that the biocontrol agents will also.

The use of the resistant cultivar combined with predators has proved beneficial in reducing insect numbers. Wiseman et al (53) found that populations of *Orius insidiosus* (Say), a predator of corn earworm larvae, were higher on a tolerant 471-U6 × 81-1 sweet corn hybrid than on susceptible ones, indicating compatibility of the effects of varietal resistance and the predator. Isenhour et al (18) found that prey feeding on a resistant cultivar resulted in a significant benefit to *O. insidiosus* as a predator of fall armyworm and corn earworm larvae. They demonstrated that the use of a resistant cultivar increased the functional response of *O. insidiosus.* The effect of larval feeding on a resistant host plant was that it slowed larval growth; thus the predator was able to prey on older larvae, while the larvae that fed on susceptible cultivars were too large for the predator to attack.

Hamm and Wiseman (11) showed that the susceptibility of fall armyworm to a nucleopolyhedrosis virus was inversely related to the growth and vigor of the larvae, which was directly related to the susceptibility or resistance of the host plant. They concluded that the virus was more effective in controlling fall armyworm larvae when used on a resistant cultivar, thus demonstrating that both the virus and the resistant cultivar were beneficial in an integrated pest management system. More recently, we found that Elcar (nucleopolyhedrosis virus) and the silk resistance to corn earworm could be combined effectively to enhance the control of corn earworm larvae (49). We found that when the corn earworm larvae fed on the resistant silks, their growth was severely stunted, and that Elcar could more effectively kill neonates (Fig. 3), as well as larvae 4 and even up to 8 days old (Table 6). Elcar caused 98 and 87% mortality of 4- and 8-day-old corn earworm larvae fed on resistant silks, as opposed to 69 and 3% mortality, respectively, of those fed control diets for 4 and 8 days (Table 6).

Plant resistance and inherited sterility. Carpenter and Wiseman (4,5) found that plant resistance to both fall armyworm and corn earworm, and inherited sterility of the two insects were compatible control strategies for the management of the two pests.

Plant resistance and cultural control. The advantages that farmers obtain from cultural methods of controlling insect pests would certainly be greater when combined with growing resistant crop cultivars. Adkisson and Dyck (1) stated that resistant varieties, including those that can be manipulated to evade pest attack, are highly desirable in a cultural control system to maintain pest populations below the economic threshold and to preserve the natural enemies. The use of early plantings in combination with resistant cultivars has been recommended for many years to avoid insect attack for crops such as wheat, cotton, sorghum, and corn. Crop rotation as a form of cultural control to avoid damaging populations of the corn rootworm, *Diabrotica* spp., has been used in the corn belt for many years. Recently, early mechanical harvesting and drying of field-infested corn reduced the abundance of the maize weevil, *Sitophilus zeamais* Motschulsky, as the grain was put in storage (19). There were also fewer weevils on corn resistant to the weevil than on corn susceptible to it. Thus, the use of weevil-resistant corns, early harvesting, and drying would complement each other in reducing the number of weevils in corn entering storage.

Table 6. Control of 4- and 8-day-old corn earworm larvae with Elcar and resistant corn silks[a]

4 Days					8 Days					
Wt. (mg)		Mortality			Wt. (mg)			Mortality		
NS	RS	NS		RS	NS		RS	NS		RS
24.1	3.6	69	*	98	557.6	*	20.2	3	*	87

[a]Weights of larvae or percent mortality separated by * are significantly different ($P < 0.05$). NS = No resistant silk. RS = Resistant silk. (Source: Wiseman and Hamm [49]).

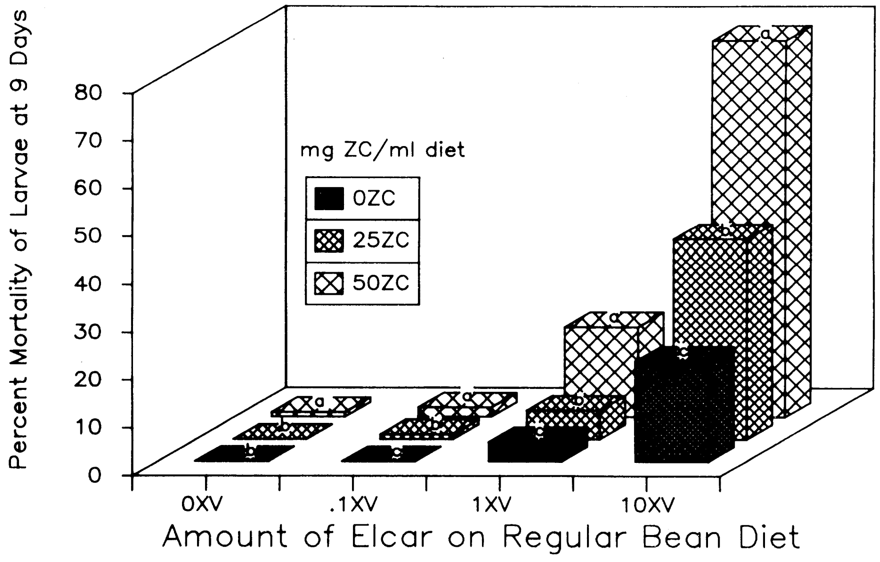

Fig. 3. Control of corn earworm neonates with Elcar after the larvae were fed on resistant corn silks (49).

Conclusions

This discussion has shown that plant resistance, in the classical sense or as transgenic plants, used by itself is effective in a number situations in controlling insect damage and/or numbers. It has also been demonstrated that plant resistance and IPM components can enhance the control of insect pests. So why don't we see more integrated systems in action? Teetes (45) identified a number of reasons for the limited impact that resistant cultivars have had in crop production: 1) failure of entomologists and plant breeders to complete their work after locating or developing an insect resistant germ plasm; 2) failure of growers to accept and use insect resistant cultivars; 3) the insecticide crunch; 4) separation of crop production and crop protection; and 5) failure to produce and distribute adequate information about the pest and the resistant cultivar. These may be the reasons we do not see a general use of integrated management of pests, nematodes, diseases, and weeds today. However, the use of a resistant cultivar, either singly or multiply resistant (to insect pest, nematode, disease, and weed), alone or in combination with other integrated pest management systems, provides crop protection that is biologically, ecologically, economically, and socially feasible (45). The resistant cultivar, not the susceptible one, is the base from which decisions must be made.

LITERATURE CITED

1. Adkisson, P. L., and Dyck, V. A. 1980. Resistant varieties in pest management systems. Pages 233-251 in: Breeding Plants Resistant to Insects. F. G. Maxwell and P. R. Jennings, eds. John Wiley & Sons, New York.

2. Buntin, G. D., and Raymer, P. L. 1989. Hessian fly (Diptera:Cecidomyiidae) damage and forage production of winter wheat. J. Econ. Entomol. 82:301-306.
3. Campbell, B. C., and Duffey, S. S. 1979. Tomatine and parasitic wasps: Potential incompatibility of plant antibiosis with biological control. Science 205:700-702.
4. Carpenter, J. E., and Wiseman, B. R. 1992. *Spodoptera frugiperda* (Lepidoptera:Noctuidae) development and damage potential as affected by inherited sterility and host plant resistance. Environ. Entomol. 21:57-60.
5. Carpenter, J. E., and Wiseman, B. R. 1992. Effects of inherited sterility and insect resistant dent-corn silks on *Helicoverpa zea* (Lepidoptera:Noctuidae) development. J. Entomol. Sci. 27:413-420.
6. Cate, J. R., Bottrell, D. G., and Teetes, G. L. 1973. Management of the greenbug on grain sorghums. I. Testing foliar treatments of insecticides against greenbug and corn leaf aphid. J. Econ. Entomol. 66:945-951.
7. Dahms, R. G. 1972. The role of host plant resistance in integrated insect control. Pages 152-167 in: The Control of Sorghum Shoot Fly. M. G. Jotwani and W. R. Young, eds. Oxford and IBH, New Delhi, India.
8. Fernandez, A. T., Graham, H. M., Lukefahr, M. J., Bullock, H. R., and Hernandez, N. S., Jr. 1969. A field test comparing resistant varieties plus applications of polyhedral virus with insecticides for control of *Heliothis* spp. and other pests. J. Econ. Entomol. 62:173-177.
9. Gallun, R. L., and Khush, G. S. 1980. Genetic factors affecting expression and stability of resistance. Pages 63-85 in: Breeding Plants for Resistance to Insects. F. G. Maxwell and P. R. Jennings, eds. John Wiley & Sons, New York.
10. Glass, E. H. 1975. Integrated pest management. Rationale, potential, needs, and implementation. Entomol. Soc. Am. Spec. Publ. 72-2.
11. Hamm, J. J., and Wiseman, B. R. 1986. Plant resistance and nuclear polyhedrosis virus for suppression of the fall armyworm (Lepidoptera:Noctuidae). Fla. Entomol. 69:541-549.
12. Havens, J. N. 1792. Observations on the Hessian fly. N.Y. Soc. Agric. Trans., Arts Manufacturing. 1:89-107.
13. Headley, J. C. 1979. Economics of pest control: Have priorities changed? Farm Chem. 142:55-57.
14. Horber, E. 1972. Plant resistance to insects. USDA Agric. Sci. Rev. 10:1-18.
15. Horber, E. 1980. Types and classification of resistance. Pages 63-85 in: Breeding plants resistant to insects. F. G. Maxwell and P. R. Jennings, eds. John Wiley & Sons, New York.
16. Isenhour, D. J., and Wiseman, B. R. 1987. Foliage consumption and development of the fall armyworm (Lepidoptera:Noctuidae) as affected by the interactions of a parasitoid, *Campoletis sonorensis* (Hymenoptera:Ichneumonidae), and resistant corn genotypes. Environ. Entomol. 16:1181-1184.
17. Isenhour, D. J., and Wiseman, B. R. 1989. Parasitism of the fall armyworm (Lepidoptera:Noctuidae) by *Campoletis sonorensis* (Hymenoptera:Ichneumonidae) as affected by host feeding on silks of *Zea mays* L. cv. Zapalote Chico. Environ. Entomol. 18:394-397.
18. Isenhour, D. J., Wiseman, B. R., and Layton, R. C. 1989. Enhanced predation by *Orius insidiosus* (Hemiptera:Anthocoridae) on larvae of *Heliothis zea* and *Spodoptera frugiperda* (Lepidoptera:Noctuidae) caused by prey feeding on resistant corn genotypes. Environ. Entomol. 18:418-422.
19. Keever, D. W., Wiseman, B. R., and Widstrom, N. W. 1988. Effects of threshing and drying on maize weevil populations in field-infested corn. J. Econ. Entomol. 81:727-730.
20. Kendrick, J. B., Jr. 1978. Agriculture's most important battle. Calif. Agric. 32:3.
21. Kennedy, G. G., Farrar, R. R., Jr., and Kashyap, R. K. 1991. 2-Tridecanone-glandular trichome-mediated insect resistance in tomato: Effect on parasitoids and predators of *Heliothis zea.* Pages 150-165 in: Naturally Occurring Pest Bioregulators. P. A. Hedin, ed. ACS Symposium Ser. 449. Am. Chem. Soc. Washington, D.C.
22. Knipling, E. F. 1966. "Introduction" to pest control by chemical, biological, genetic, and physical means. Symp. U.S. Agric. Res. Serv. [Rep.] ARS 33-110. pp 1-3.
23. Kogan, M., and Ortman, E. E. 1978. Antixenosis–a new term proposed to replace Painter's "nonpreference" modality of resistance. Entomol. Soc. Am. Bull. 24:175-176.
24. Koziel, M. G., Beland, G. L., Bowman, C., Carozzi, N. B., Crenshaw, R., Crossland, L., Dawson, J., Desai, N., Hill, M., Kadwell, S., Launis, K., Lewis, K., Maddox, D., McPherson, K., Meghji, M. R., Merlin, E., Rhodes, R., Warren, G. W., Wright, M., and Evola, S. V. 1993. Field performance of elite transgenic maize plants expressing an insecticidal protein derived from *Bacillus thuringiensis.* Bio/Technology 11:194-200.
25. Luginbill, P., Jr. 1969. Developing resistant plants–the ideal method of controlling insects. USDA-ARS Prod. Res. Rpt. 111.
26. Maxwell, F. G. 1972. Host plant resistance to insects–nutritional and pest management relationships. Pages 599-690 in: Insect and Mite Nutrition. North-Holland Publishing Co., Amsterdam.
27. McMillian, W. W., and Wiseman, B. R. 1972. Host plant resistance: A twentieth century look at the relationship between *Zea mays* L. and *Heliothis zea* (Boddie). Fla. Agric. Exp. Stn. Monogr. Ser. 2.
28. McMillian, W. W., Wiseman, B. R., Widstrom, N. W., and Harrell, E. A. 1972. Resistant sweet corn hybrid plus insecticide to reduce losses from corn earworms. J. Econ. Entomol. 65:229-231.
29. Overman, J. L. 1989. A maize breeding program for development of hybrids with resistance to multiple species of leaf-feeding and stalk-boring lepidoptera. Pages 235-243 in: Toward insect resistant maize for the third world: Proc. Int. Symp. Methodol. Dev. Host Plant Resist. Maize Insects. CIMMYT, Mexico, D.F.
30. Owens, J. 1975. An explanation of terms used in insect resistance to plants. Iowa State J. Res. 49:513-517.
31. Painter, R. H. 1951. Insect resistance in crop plants. MacMillan Co, New York.
32. Painter, R. H. 1958. Resistance to insects. Annu. Rev. Entomol. 3:267-290.
33. Painter, R. H. 1966. Plant resistance as a means of controlling insects and reducing their damage. Pages 138-148 in: Pest control by chemical, biological, genetic, and physical means–a symposium. USDA-ARS-33-110, U.S. Dep. Agric.
34. Painter, R. H. 1968. Crops that resist insects provide a way to increase world food supply. Kans. Agric. Exp. Stn. Bull. 520.
35. Pair, S. D., Wiseman, B. R., and Sparks, A. N. 1986. Influence of four corn cultivars on fall armyworm (Lepidoptera:Noctuidae) establishment and parasitism. Fla. Entomol. 69:566-570.
36. Pedigo, L. P. 1975. Insect threats and challenges to Iowa agroecosystems. Iowa State J. Res. 49:457-466.
37. Reissig, W. H., Heinrichs, E. A., and Valencia, S. L. 1982. Insecticide-induced resurgence of the brown planthopper, *Nilaparvata lugens,* on rice varieties with different levels of resistance. Environ. Entomol. 11:165-168.
38. Roberts, J. J., Foster, J. E., and Patterson, F. L. 1988. The Purdue-USDA small grain improvement program–a model of research productivity. J. Prod. Agric. 1:239-241.
39. Schalk, J. M., and Ratcliffe, R. H. 1976. Evaluation of ARS programs on alternative methods of insect control: Host plant resistance to insects. Bull. Entomol. Soc. Am. 22:7-10.
40. Smith, C. M. 1989. Plant Resistance to Insects: A Fundamental Approach. John Wiley & Sons, New York.
41. Smith, E. H. 1992. The grape phylloxera–a celebration of its own. Am. Entomol. 38:212-221.
42. Smith, R. F. 1978. Development of integrated pest management in California. Calif. Agric. 32:5.
43. Starks, K. J., Muniappan, R., and Eikenbary, R. D. 1972. Interaction between plant resistance and parasitism against the greenbug on barley and sorghum. Ann. Entomol. Soc. Am. 65:650-655.
44. Starks, K. J., Wood, E. A., Jr., and Burton, R. L. 1974. Relationships of plant resistance and *Lysiphlebus testaceipes* to population levels of the greenbug on grain sorghum. Environ. Entomol. 3:950-952.
45. Teetes, G. L. 1985. Insect resistant sorghums in pest management. Insect Sci. Appl. 6:443-451.
46. Vanderplank, J. E. 1963. Plant diseases: Epidemics and control. Academic Press, New York.
47. Vanderplank, J. E. 1968. Disease resistance in plants. Academic Press, New York.
48. Wiseman, B. R. 1982. The importance of *Heliothis*–crop interactions in the management of the pest. Pages 209-222 in: Proc. Int. Workshop *Heliothis* Manage., 1981. International Crops Research Institute for the Semi-Arid Tropics, Patancheru, A. P. India.
49. Wiseman, B. R., and Hamm, J. J. 1993. Elcar and resistant corn silks enhance mortality of corn earworm (Lepidoptera:Noctuidae) larvae. Biol. Control. 3:337-342.
50. Wiseman, B. R., Harrell, E. A., and McMillian, W. W. 1973. Continuation of tests of resistant sweet corn hybrid plus insecticides to reduce losses from corn earworm. Environ. Entomol. 2:919-920.
51. Wiseman, B. R., and Isenhour, D. J. 1990. Effects of resistant maize silks on corn earworm (Lep.:Noct.) biology: A laboratory study. J. Econ. Entomol. 83:614-617.
52. Wiseman, B. R., McMillian, W. W., and Widstrom, N. W. 1972. Tolerance as a mechanism of resistance in corn to the corn earworm. J. Econ. Entomol. 65:835-837.
53. Wiseman, B. R., McMillian, W. W., and Widstrom, N. W. 1976. Feeding of corn earworm in the laboratory on excised silks of selected corn entries with notes on *Orius insidious.* Fla. Entomol. 59:305-308.
54. Wiseman, B. R., Widstrom, N. W., and McMillian, W. W. 1981. Effects of 'Antigua 2D-118' resistant corn on fall armyworm feeding and survival. Fla. Entomol. 64:515-519.
55. Wiseman, B. R., Widstrom, N. W., and McMillian, W. W. 1984. Increased seasonal losses in field corn to corn earworm. J. Ga. Entomol. Soc. 19:41-43.
56. Yanes, J., Jr. and Boethel, D. J. 1983. Effect of a resistant soybean genotype on the development of the soybean looper (Lep.:Noct.) and an introduced parasitoid, *Microplitis demolitor* Wilkinson (Hymenop.:Brac.). Environ. Entomol. 12:1270-1274.