Editor's note: This article is a companion piece to the article by Charles Silcox and Patricia Vittum on modes of action of insecticides, which appeared in the September 2008 issue of GCM. *Both articles are based on information that was presented by the authors in an educational seminar at the January 2008 GCSAA Education Conference in Orlando.*

Development of resistance by turf insects to insecticides

Although insects are beginning to show resistance to insecticides, superintendents can manage products to extend their usefulness.

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Over the years, superintendents have become aware of situations in which various fungal pathogens have developed resistance to certain fungicides. The same phenomenon is beginning to occur with populations of some turf insect species, which are developing resistance to some insecticides. In this article, we will discuss the concept of resistance, explain the importance of understanding the mode of action of turf insecticides, provide a case study of a turf insect that has recently developed resistance to at least one group of insecticides, and provide some practical suggestions to minimize the likelihood that a pest population develops resistance.

What is resistance?

Sometimes a superintendent uses a certain insecticide repeatedly to manage an insect population. Often the product continues to work well for many seasons, but in some cases a more critical view of the situation indicates that the product is not as "effective" (does not kill as high a percentage of the population) following several seasons of repeated use as it was when the product was first used against that insect species. For the purposes of illustration, consider a situation in which a superintendent uses chemical X to control a turf insect problem in the first year the chemical comes to the turf market. Chemical X is labeled for application at 1 pound active ingredient per acre (1 pound a.i./acre), and can be used up to three times per year. The first year the superintendent uses the product, the insect population is greatly reduced (at least 90% control). The product seems to remain active for at least three months, and only one application is needed to do the job.

Because the product seemed so effective, the superintendent orders more for the next season and achieves similar results. By the third or fourth year of repeated use of chemical X, however, the superintendent notices that a lower percentage of

Reduced activity of pyrethroids on annual bluegrass weevil was first reported in Connecticut. **Photos by Steve McDonald** the insects seem to be controlled as a result of the application or, alternatively, that the product does not remain active for as many weeks as it did at first. So the superintendent starts to experiment and applies the product twice, at three-week intervals, in an effort to control the insect population. (This scenario no doubt sounds very familiar to those who have been trying to manage dollar spot recently.)

When we get to this point, one possible explanation is that the insect population has developed resistance to chemical X. *Resistance* can be defined as a loss of field effectiveness, usually as a result of repeated applications. In our example, the superintendent initially applied chemical X at 1 pound a.i./acre, but perhaps by the fourth year of using the product discovered that repeated applications or heavier application rates (when allowed by the label), totaling 4 or 5 pounds a.i./acre per season, failed to achieve the same level of control.

Laboratory studies

Laboratory studies often can be conducted to track the development of resistance in insect populations. Richard Cowles, Ph.D. (Connecticut Agricultural Experiment Station), first reported reduced activity of pyrethroids toward populations of annual bluegrass weevil (*Listronotus maculicollis*) on golf courses in Connecticut where pyrethroids had been used extensively for many years. Steven Alm, Ph.D. (University of Rhode Island), and his graduate student Darryl Ramoutar recently have been working in collaboration with Cowles to assess pyrethroid resistance by annual bluegrass weevils on a number of golf courses in Connecticut. Their results to date show pyrethroid resistance ratios that vary from 37 to 112 on courses with a history of extensive pyrethroid applications. A "resistance ratio" can be calculated as the concentration needed to control a resistant population divided by the concentration needed to kill a susceptible population. (For example, a resistance ratio of 37 means that it took 37 times as much product to kill the same percentage of the resistant population as it did to kill a susceptible population.) This research documents that the effectiveness of the pyrethroids has declined significantly in the resistant populations.

Field studies

Laboratory studies do not always reflect what is observed in field conditions. For example, one population of annual bluegrass weevils near Hartford, Conn., showed a resistance ratio of 97. But the same year that laboratory trial was conducted, one of us (PJV) conducted a field trial of several insecticides on the same golf course, including the same pyrethroid, and observed 92% control of the field population. There are several possible explanations, but the main point is that laboratory studies can serve as indicators of what is happening, but they do not always provide an accurate prediction of what kind of field control will be achieved when resistance first begins to develop in an area.

Insects with a genetic mutation that protects them from the effects of an insecticide are more likely to survive and pass on their "lucky" gene to their offspring.

How does resistance develop?

Resistance often first appears in an insect population simply because some individuals are "lucky" and have a genetic mutation that protects them from the harmful effects of the insecticide. So when chemical X is applied to the population, the ones with the "lucky" genes survive, whereas a large proportion of the "unlucky" (susceptible) individuals are killed. Over time, there is a shift in the insect population. Perhaps originally only 1% of the population had the gene that confers resistance, but when chemical X is applied, that 1% is at a distinct advantage. Those individuals will be much more likely to survive and be in a position to pass on their "lucky" genes to their offspring.

Often the resistance gene provides an obvious advantage whenever chemical X is present, but it also may have a cost associated with it. The insect that carries the resistance gene may take longer to develop from egg to adult, or it may be less efficient at converting food to energy or less successand when the insects were exposed to the insecticide, the resistance gene provided enough of a survival advantage that the individuals with the gene survived and multiplied.

Resistance development

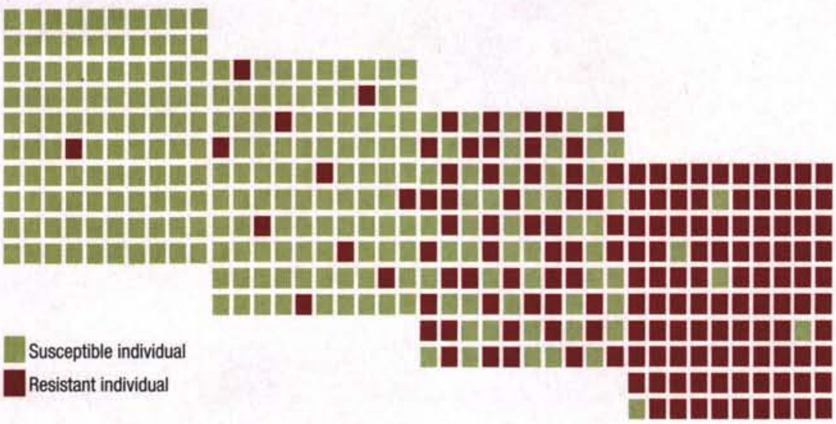

Figure 1. Resistance often appears in a population because one or more members are "lucky" (represented by the red squares) and have a gene that imparts resistance to an insecticide. The rest of the population is not as "lucky" and is susceptible to the insecticide (green squares).

ful at competing for mates. However, as long as chemical X is in the population's environment, that resistance gene will provide an overriding advantage for the insects that have it.

Figure 1 demonstrates the concept of the development of resistance. For the purposes of illustration, we assume that 1% of the original population of insects has the resistance gene (red squares) and they all survive an application of chemical X, while 99% of the susceptible population (green squares) is killed. The second generation has noticeably more insects carrying the resistance gene and fewer susceptible individuals. If we apply chemical X again, the resistance gene becomes even more prominent. And if we apply chemical X yet again, almost all of the fourth generation is resistant to the chemical.

Normally, the transition from a susceptible population to a resistant population does not occur nearly this quickly, at least with the insecticides we have used in turf for the past 20 years or so. However, some insect populations in other crops have developed resistance to certain insecticides after only one or two exposures. The Colorado potato beetle developed resistance to imidacloprid in several different parts of the U.S. after only a couple of years of widespread use. This suggests that the genetic makeup of the Colorado potato beetle had an inherent "resistance gene" in the population,

Which conditions are most likely to lead to resistance?

Much of resistance development is driven by genetic variation. In essence, the more offspring produced, the greater the chance that at least some of those offspring will have a gene that provides resistance against chemical X. Therefore, it makes sense that resistance often shows up in insects that have a relatively high reproductive capacity. In general, sexual reproduction will provide more opportunity for genetic mixing. Insect species that produce relatively large numbers of offspring each generation or have several generations per year have more opportunity to produce at least a few individuals that have a "lucky" gene that provides resistance. It's a numbers game!

Conditions that lead to resistance

- Relatively high reproductive capacity
- Multiple generations per year
- Limited host range and mobility
- Few insecticides that work, or few modes of action that work
- Multiple applications each year, many of which disrupt natural enemies

Individuals with high populations are more likely to develop resistance.

Feeding habits

Meanwhile, if an insect population feeds on only one or two kinds of plants, it is more likely to develop resistance to an insecticide. Usually, if only one or two species of plants are attacked by the insect and those plants are being protected by the insecticide, the insect has no other place to go to avoid exposure to the insecticide. Susceptible individuals will be controlled and resistant individuals will survive.

Lack of mobility

Similarly, if the insect is not very mobile, it is more likely to develop resistance. If the insect is not able to move away from the treated area, the susceptible individuals will experience the harmful effects of the insecticide and be eliminated. In addition, if the insect population is not very mobile, there is also no chance for other susceptible individuals to migrate into the treated area and dilute the effect of the resistance gene by increasing the number of susceptible insects available to reproduce.

How much turf is treated?

Another variation on the theme relates to the amount of treated turf. When an insecticide is applied wall-to-wall on several golf courses and by most other turf managers in a given area, most of the susceptible insects in that area will be killed and most of the resistant individuals will survive. If the treated areas are large enough, susceptible individuals will have little opportunity to move in from other areas. If only heavily infested areas are treated, the untreated areas become *refuges,* areas where the susceptible individuals can survive. It may seem counterintuitive, but this can be a good thing. If some susceptible insects survive, they can mate with the resistant individuals and slow the development of resistance.

Currently 12 chemical classes of insecticides are used in turfgrass management. Each of these has a specific *mode of action* (that is, the way the chemical actually affects the insect). Many of the older insecticides are nerve poisons, affecting the transmission of electrical impulses from one nerve cell to another. (These different modes of action are described in some detail in the September 2008 issue of *GCM.*) Insects usually do not differentiate between different insecticides with the same mode of action. For example, the pyrethroids all have the same mode of action: They interfere with the movement of sodium and potassium ions along the nerve cell membrane. If an insect develops resistance to one pyrethroid, it ordinarily develops resistance to all the other pyrethroids at the same time. This phenomenon is known as *cross-resistance.* In addition, some insects will develop resistance to insecticides in different chemical classes or with more than one mode of action. This is called *multiple resistance.* (Houseflies developed resistance to many different modes of action within a few years of exposure when synthetic insecticides first were used in the late 1940s and 1950s.)

If an insecticide is applied wall-to-wall on several golf courses and other turf sites in a given area, most of the susceptible insects within that area will be killed, allowing mainly the resistant insects to survive. **Photo by P. Vittum**

If only one or two classes of insecticides have been shown to be effective against a pest population, there can be considerable pressure on that population to develop resistance to one or both of those classes. In other words, if we keep using only one or two classes or modes of action to control a population of insects, it increases the chances that some individuals will have the "lucky" gene and develop resistance to that mode of action, while susceptible individuals will be eliminated.

Each time an insecticide is used, it puts pressure on the target population to develop resistance. So it stands to reason that multiple applications of chemicals with the same mode of action during a growing season will speed the process. Each generation has the potential to produce some individuals that are resistant to the chemical, and each application of the chemical puts more pressure on that population, giving an advantage to the insects with the "lucky" gene and putting the susceptible individuals at a disadvantage.

We can also speed the process of developing resistance by applying an insecticide in such a way that two different generations of an insect population are exposed to the insecticide as a result of a single application. An example would be applying one of the neonicotinoids to turf in mid-spring in the Northeast as a preventive control of white grubs later in the season. Some superintendents justify such an application because it can provide control of other insects during late spring and early summer, but the application would result in exposure to the white grubs that are present after the winter before they pupate (the spring generation), and the chemical would still be present in the soil when the new young grubs emerge from the next generation. Although there is no evidence yet that any turf insects have developed resistance to a neonicotinoid, other agricultural pests have developed resistance to insecticides in that class, and we might be wise to avoid use patterns that would speed the process.

Historically, use of insecticides that are very persistent has often led to the development of resistance. If we use an insecticide that remains active for several months or — in the case of DDT, chlordane and their relatives — several years, the insect population is under constant pressure to develop resistance. In fact, more than 100 species of insects developed resistance to DDT shortly after it was introduced to agriculture, in part because the populations were under constant pressure. Only the adaptive ones survived.

Case study: annual bluegrass weevil

The annual bluegrass weevil (*Listronotus maculicollis*) is primarily a golf course pest on annual bluegrass (*Poa annua*) in the northeastern U.S. Sometimes called the "Hyperodes weevil," it feeds primarily on annual bluegrass on fairways, greens or tees, but occasionally is active on creeping bentgrass (*Agrostis stolonifera*) as well. Adults move short distances in the spring, mainly by walking, and return to overwintering sites in autumn. It completes three or four generations per year in the metropolitan New York area. Some superintendents treat greens as many as six times per year to manage the populations.

Resistance is more likely to occur in insects like annual bluegrass weevil that are not very mobile. Annual bluegrass weevil adults may walk short distances in the spring and then fly to protected overwintering sites, often along defined tree lines. **Photo by Steve McDonald**

From the early 1970s until the mid-1990s, Dursban (chlorpyrifos) was used as a preventive treatment, applied when dogwood reached full bloom to target adults before they had a chance to lay eggs. As pyrethroids became available in the 1990s, they began to replace Dursban as the preventive treatment.

For several years, the insecticide of choice has been one of the pyrethroids, and since fall 2005, Rich Cowles has documented pyrethroid resistance in annual bluegrass weevils in several locations in the Northeast. Many superintendents also have reported "failures" of pyrethroids in field conditions, and in some of those cases, laboratory studies have documented resistance (resistance ratios of 35 or more).

We believe the annual bluegrass weevil is a prime candidate for developing resistance to pyrethroids because most of the "conditions" are present. It has a relatively high reproductive capacity (each female produces 30 to 50 eggs), the insect completes several generations per year even in the Northeast, it has limited host range and mobility, very few insecticides have been effective against the adults over the years, and superintendents have made multiple applications of the same chemical class (pyrethroids) each year for many years. Perhaps the surprise is that resistance did not become apparent until recently.

How can superintendents manage resistant populations of annual bluegrass weevils? First and foremost, those who are dealing with resistant populations need to minimize their reliance on pyrethroids. For example, they can substitute chlorpyrifos (an organophosphate) when targeting adults. In addition, they need to monitor the affected areas much more intensively than in previous seasons and use products that are effective against larvae as soon as the larvae become apparent. Several products, including Dylox (trichlorfon, Bayer), Conserve (spinosad, Dow AgroSciences) and Provaunt (indoxacarb, DuPont Professional Products), have been shown to be effective against larvae if they are applied when larvae are still fairly small. It is very encouraging to note that some new insecticides on the market have new modes of action and have shown activity against annual bluegrass weevils. These include Provaunt and Acelepryn (chlorantraniliprole, DuPont Professional Products).

Several other nonchemical strategies can be incorporated to minimize weevil populations or to enhance turf vigor. These include minimizing annual bluegrass (with plant growth regulators or watering or mowing strategies), minimizing the stress on the annual bluegrass, or disrupting overwinter sites. A suggestion, so far untested, has been made to incorporate barrier strips between the overwintering sites and the fairway or greens or tees, thereby making it more difficult for weevils to return to the short-cut areas in the spring.

Ways to minimize or delay the development of resistance

Most of the management strategies that superintendents can incorporate to delay the development of resistance are common sense. In essence, the primary focus needs to be on minimizing applications of insecticides that have shown a tendency to lead to resistance. This is often easier said than done, because for some insects, there are relatively few options available. However, there is new chemistry entering the market and with attention to detail, superintendents should be able to incorporate new strategies and slow the development of resistance.

The rest of the common sense is related to good cultural practices. Any activity that reduces stress on the turf (for example, mowing heights and patterns, watering, fertility) enables that turf to tolerate more insect activity. If the tolerance level is increased, then insecticides often can be used less often or less aggressively.

Chemical strategies to delay the development of resistance

Three basic approaches could be considered when determining a strategy to maximize the effectiveness of an insecticide and delay the development of resistance in pest populations. One approach that has been proposed by at least one turf pathologist is to use a given product (or class of chemicals with a similar mode of action) until it no longer is effective. Most turf entomologists do not support this approach, but we have seen situations (the annual bluegrass weevil), where superintendents felt like they had no other alternatives.

Repeated use of a single chemical class or mode of action seldom makes sense in the long term for managing insect populations. But we can try to incorporate at least a couple of different modes of action into the action plan. One way to accomplish this is to combine two different modes of action into a single application ("tank mix"). The theory is that while some of the insects in the target population might be resistant to chemical A, they probably would not also have a gene conferring resistance to chemical B. Similarly, some might be resistant to chemical B, but not chemical A. So a combination of the two chemicals in one application would, presumably, eliminate a high proportion of the insects in that population. Although we do not have field data to support that hypothesis, the combinations seem to provide excellent levels of field efficacy in many cases.

Some turf entomologists have a philosophical difficulty with a popular tank mix that has recently entered the turf market. Allectus (Bayer Environmental Science) was the first combination product to be marketed, combining Merit (imidacloprid) and Talstar (bifenthrin). The combination of a neonicotinoid and a pyrethroid was originally developed for the lawn-care market and has been very well received in many parts of the country. Aloft (Arysta LifeScience), a combination of Arena (clothianidin) and a generic form of bifenthrin, joined the market about a year later. Some superintendents make their own combinations with one of the three neonicotinoids (chlothianidin, imidacloprid or thiamethoxam) and one of the several pyrethroids (bifenthrin, cyfluthrin, lambda-cyhalothrin, deltamethrin and others).

For some of the pest complexes, and particularly for lawn-care operators, the combination enables a superintendent to make a single well-timed application that targets many different turf insects and often reduces the need for "call backs." The "philosophical difficulty" arises when the combination product is applied in late spring to golf courses when overwintering white grubs are still present. This ensures that two different generations of grubs will be exposed to the application, which could perhaps speed the development of resistance. (Again, resistance to neonicotinoids has not been documented in any turf insect pest, but we might be wise to be cautious or conservative, and try to avoid repeated applications in this manner.)

A slightly different approach is to alternate chemical classes or modes of action. In the example above, a superintendent might apply chemical A and then come back the next time (a few weeks or months or a year later, depending on the life cycle of the target insect) with chemical B. Over the years, this approach has often worked very well, but until recently, superintendents who were trying to use preventive treatments to control white grubs found their options were limited

The research says

→ When the efficacy of an insecticide seems to decline, one possible explanation is that the insect has developed *resistance* to the insecticide.

→ A genetic mutation may protect some individuals so that they are resistant to a particular insecticide; resistant individuals survive insecticide exposure to reproduce offspring that are also resistant, making the resistance gene more prominent in the population.

→ Resistance is more likely in insects that have a high reproductive capacity, feed on only one or two kinds of plants and lack mobility.

→ Resistance is also more likely when few insecticides or modes of action are available to control the insect and multiple applications are made each year.

→ Resistance can be delayed by limiting the number of applications of a single product or of pesticides with a single mode of action.

to neonicotinoids. No other modes of action or classes of chemicals worked consistently, particularly in the Northeast where oriental beetles are active. Although superintendents usually understand the importance of alternating chemicals, at times they have not had many good choices.

What lies ahead?

We believe the future looks bright for insecticide management in turf. For the first 50 years that synthetic chemicals were available (Figure 2), superintendents relied on only two or three chemical classes, but in the past 15 to 20 years, several new modes of action have been developed and commercialized. As long as superintendents and other turf managers use these chemicals wisely and incorporate many different modes of action into their insect management plans, the effective life span of each product should be maximized. In addition, the newer chemistries are much less toxic to vertebrates and other nontarget organisms — another little bonus!

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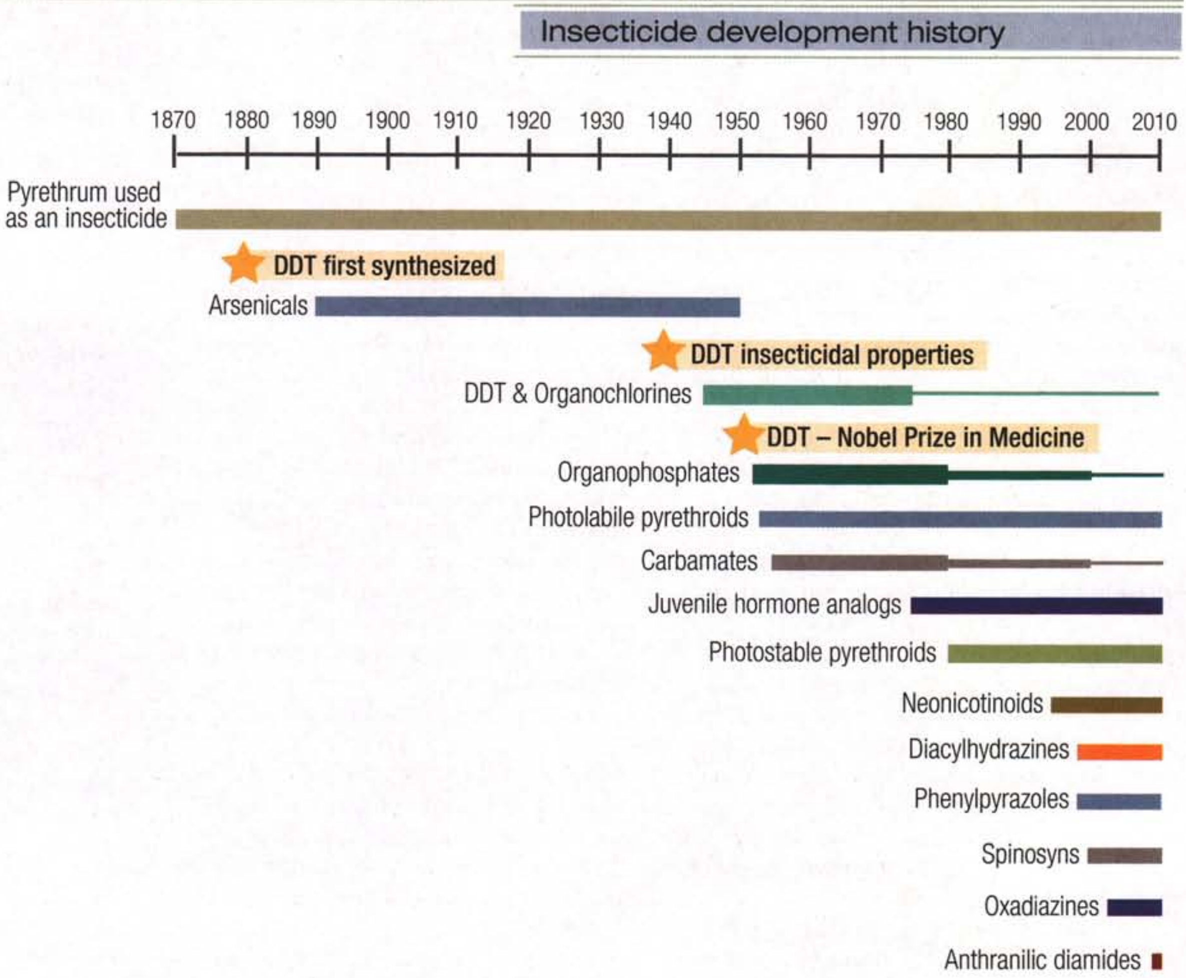

Figure 2. A timeline of the history of insecticide development from the late 1800s to the present.