AVIAN REPELLENTS

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The use of repellents to protect crops from birds has a long history. Early European settlers in eastern North America observed that native Americans used an extract of *Veratrum* spp. to protect corn seeds from avian depredators: "Then when the starlings, crows, or other birds, pick up or pluck out the grains of corn, their heads grow delirious, and they fall, which so frightens the rest that they never venture on the field again. When those which have tasted the grains recover, they leave the field, and are no more tempted to visit it again" (1).

Repellents move birds from one place to the next. After successful application of a bird repellent, the overall amount damage will probably not decrease, but it will be distributed differently. Some persons are philosophically opposed to repellents because they do not reduce damage overall, but instead shift the problem to a neighbor's field or vineyard. However, by definition, repellents are nonlethal and as such they represent a very appealing approach to the management of bird damage in crops (2). Bird damage is usually highly skewed among sites, with most producers incurring little damage and few suffering high, economically important levels of damage (3). Realistically, the goal of bird damage management is not to eliminate losses, but to reduce them to an acceptable, manageable level. To the extent that a repellent can help redistribute the economic impact among producers, and especially provide relief at the few high-damage sites, it will be a successful component of bird damage management plans.

FORAGING THEORY AND CHEMICAL REPELLENTS

Birds attack crops because they are readily accessible sources of abundant food obtainable with low expenditure of effort. This is especially important to young birds that are not experienced foragers. In the late summer and fall, newly fledged birds constitute a large portion of many depredating flocks. Because of the availability of large quantities of food, crop fields, vineyards, and orchards provide ideal feeding situations for young birds just learning to fend for themselves. At other times of year, sources of the birds' natural food may be limited or lacking altogether so that the cultivated crop becomes an essential component of diet (4). The continuing alteration of the natural landscape to accommodate human population expansion will no doubt make it increasingly difficult for birds to find natural sources of food. Given this situation, it is easy to appreciate why agricultural crops are powerful attractions to bird and why depredating birds are not easily dissuaded. With the potential benefits of feeding on the crop so great, there must be a commensurately high potential cost in order to discourage bird use of the protected food.

To be effective, a chemical repellent must affect the way that the bird perceives the crop. For most depredating birds, the benefits to feeding on the crop far outweigh the costs. The challenge is to alter that balance so that either the benefits are greatly reduced or the costs are greatly increased. Basically, increasing the cost to the birds means increasing the amount of time and energy required to feed on the crop. The more time the bird has to spend acquiring the requisite nutritional resources, the less time it can spend on other essential activities such as territorial defense, nest building and mate acquisition, feather maintenance, predator vigilance, and so on. There is therefore substantial pressure on the bird to feed efficiently. In most applications of optimal foraging theory, it is assumed that the animal is maximizing its rate of energy intake (5). Caloric gain is not the only nutritional requirement a bird has, but it seems to be a pervasive one. If it becomes difficult for the bird to maintain a certain rate of energy intake by feeding on the crop, then optimal foraging theory predicts the bird will look for other sources of food. Thus, the net effect of applying a chemical repellent to the crop will be to lower the value of the crop to the bird by reducing its rate of energy intake. This can be accomplished by making the preferred food more difficult to find, more difficult to handle, or more difficult to digest.

More Difficult to Find

It is not possible to hide the crop from the birds. Nor is it likely that the crop can be disguised so that it looks like something inedible. It is possible, however, to apply the concepts of mimicry theory to crop protection and combine edible, untreated parts of the crop with chemically protected, but visually identical portions of the crop (6,7). This can be accomplished by applying the chemical repellent to some of a seed crop, mixing it with an equal amount of untreated seed, and then broadcasting the mixture on the field (8). Alternatively, certain rows or individual plants in an orchard or vineyard can be sprayed with chemical repellent and the rest left untreated (9). This approach relies on the assumption that treated and untreated food items are not visually distinct. If birds are reliably able to select the untreated food, then there is no advantage to partial treatment. Also, the cost to the bird of making a mistake and selecting a treated food item must be high. Otherwise, there is no reason for the bird to avoid testing and evaluating the alternatives. The repellent treatment should cause the bird to delay its decision long enough so that the energy gained per time spent recognizing, identifying, and selecting the food item declines to where it is no longer profitable. At that point, the bird will move to other locations or search for other types of food.

More Difficult to Handle

Once the food item is selected and acquired, manipulation of the food item can constitute an important commitment

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of time and effort by the foraging bird. Intuitively, the more potentially valuable a food item is, in terms of caloric value or nutrient content, the more time the bird should be willing to spend to manipulate and consume it. Generally, as the size of the food item increases, the handling time increases as well. Although the bird might be able to eat the larger food item, the longer it takes to handle it, the greater the chances for inadvertently dropping it. Small seeds or small fruits can be ingested with virtually no manipulation. Thus, cedar waxwings (*Bombycilla cedrorum*) prefer to eat small blueberries because almost always the birds ingest the berry in seconds, whereas larger fruit that potentially yields greater caloric rewards take longer to manipulate and are often dropped and lost (10). The rate of caloric intake is greatest with the smallest size berry. As a rule, red-winged blackbirds (*Agelaius phoeniceus*) can eat rice seed at a rate of 6–8 seeds/min. The rice seed can be coated, however, with a nontoxic clay-based treatment that greatly increases the time interval between seeds taken by the blackbird (11). The sticky coating on the seed causes the bird to spend time wiping and cleaning its bill so that feeding rates are greatly reduced. As a consequence, the rate of caloric intake declines to the point that birds avoid the clay-coated rice seed (12).

More Difficult to Digest

After it is recognized, selected, manipulated, and ingested, the food item still has to be digested and assimilated if it is to benefit the bird. Modification of the food item so that it is rendered more difficult to digest will reduce its attractiveness to depredating birds. Certain phenolic compounds, generally referred to as tannins, are effective digestive inhibitors because they form insoluble precipitates with proteins, including various digestive enzymes. The resulting reduced activity of the digestive enzymes causes weight loss and other detrimental physiological effects (13). In some cereal crops such as sorghum and millet, high tannin varieties have been developed specifically for bird deterrence (14). Some frugivorous bird species, including those that cause crop damage, such as the American robin *Turdus migratorius* and the European starling *Sturnus vulgaris*, possess a physiological constraint that makes it impossible for them to digest sucrose, a common constitute of many fruits (15). These bird species lack the intestinal enzyme sucrase that hydrolyzes the 12-carbon sucrose molecule, that cannot be assimilated, into the 6-carbon sugars glucose and fructose, which are assimilable. Means of exploiting this digestive constraint so that small cultivated fruits will be less susceptible to bird damage include using sucrose as a spray on ripening fruit (16) and manipulating sugar composition of ripening fruit to produce elevated, bird-resistant levels of sucrose (17).

Alternative Food Sources

Reducing the value of the crop is one key component to repellent use. The other crucial factor is the availability of alternative sources of food. A bird with no alternatives will tolerate much greater discomfort than will one that has access to other food sources. Thus, chemical repellents will function more effectively with alternative food sources available than with no alternative. The disparity in attractiveness between the crop and potential alternative foods will determine how strong the repellent must be to protect the crop. If the foraging efficiency in the alternative is close to that in the crop, then it will be relatively easy to effect a change in the birds' behavior. Often, wild seeds or fruits are available in fields or meadows adjacent to the crop, but a number of factors reduce the relative attractiveness of an alternative food source: 1) the birds' efficiency in feeding on the wild food sources might be less than when they feed in the crop, 2) their risk of being preyed on might be higher than in the crop, 3) the intrinsic quality of the food items (for example, caloric content) might be lower than that of the crop, and 4) competition with other animals for the alternative food might be greater than in the crop. Any of these factors, individually or in combination, might be sufficient to encourage the depredating birds to prefer the crop to the alternatives. Whatever steps that can be taken to increase the birds' rate of energy intake feeding on the alternative food will likely promote more effective repellent use. One possible tactic that could constitute a part of a long-term management scheme is to provide alternative food patches specifically for avian depredators. In this way, a grower could assure that the alternative food is comparable in quality and abundant enough to satisfy the birds' requirements. Establishment of feeding sites specifically for pest birds is probably not intuitively pleasing to most producers, and the effectiveness of this management approach needs to be experimentally tested.

CATEGORIES OF CHEMICAL REPELLENTS

In general, repellents can be divided into two broad categories based on their modes of action. Primary repellents are painful or irritating upon contact, and the bird responds reflexively without needing to acquire an avoidance response. Extensive research into the nature and characteristics of dozens of primary repellents lead Clark (18) to the conclusion that chemesthesis (pain or irritation) is responsible for avoidance responses produced by these compounds. Many of these compounds have ecological significance in interactions between birds and their natural food items, and one primary repellent compound, methyl anthranilate, is registered as an avian feeding deterrent. Many primary repellents are toxic, but because the compounds are aversive, birds do not ingest enough to cause them harm.

Secondary repellents are not aversive immediately but produce illness or discomfort sometime after ingestion. The effectiveness of these compounds is based on the concept of conditioned food avoidance (19). The bird associates the adverse postingestional consequences with the food or with some sensory attribute of the food (e.g., color or taste) and thereby learns to avoid it. The avoidance response produced by a secondary repellent is likely more robust than that from a primary repellent (20,21). Secondary repellents are toxic, and for some compounds, the difference between a repellent dose and a lethal dose may be slight.

AGRICULTURE USES FOR BIRD REPELLENTS

Avian repellent compounds have potentially two general uses in agriculture: to reduce bird depredations to crops and to reduce hazards to birds posed by potentially toxic pesticides. For crop protection, both primary and secondary repellents are applicable. The situations in which one or the other will be more appropriate will vary according to a number of factors. A primary repellent will be advantageous when the birds are not resident in the area or where the population of depredating birds is not constant but changes frequently. A primary repellent requires no learning period before the effectiveness of the treatment takes effect. Birds immediately sense the chemical when they eat treated food, and they respond to the sensory irritation. Even though primary repellents require no learning to be effective, birds might tend to test the protected crop, and so additional damage may accumulate even after the same birds have been exposed to the treatment. This is especially true if the primary repellent does not produce sufficiently potent punishment to discourage bird use of a highly preferred food item such as the protected crop. There is temporary irritation from the primary repellent, but no incapacitation; so the risk to the bird is relatively minor, and it tends to continue to try the treated food items.

Because a secondary repellent produces no immediate negative consequence to the bird, there will be some continued feeding until the association is made between the treated crop and the discomfort. In field applications, the effectiveness of a secondary repellent will be determined in part by the residency status of the depredating bird population. If the birds are sedentary, then a secondary repellent will most likely be effective because the birds will be in the area a sufficient length of time to acquire the avoidance response and learn to avoid the treated crop. If, however, the birds are mostly transient, the application of a secondary repellent will not be as useful because the birds will be present just a short time. Depending on the time needed to acquire the avoidance response, the affected birds could have departed and been replaced by a different group of birds, which in turn will have to acquire the avoidance response. Damage will occur and accumulate as each new group of birds learns to avoid the repellent-treated crop.

AVAILABILITY OF BIRD REPELLENTS

Currently, crop damage reduction with chemical repellents is limited to a few registered products (22). The lack of registered bird-repellent compounds is not due to a lack of potentially useful chemicals. In recent years, many compounds have been identified as bird-repellent (Table 1). In addition to those listed in Table 1, Clark (23) has generated repellency data on dozens of other compounds. New screening methods using structure-activity modeling and tissue culture mean that candidate repellent compounds can be identified more systematically than before (24).

The main reasons for the paucity of useful bird-repellent agricultural products are lack of economic incentive and restrictions imposed by regulatory agencies. Increasingly, there is concern for the human health and environmental safety of agricultural chemicals. These concerns have resulted in more extensive and stringent testing requirements, which have elevated the costs of chemical registration considerably. In most cases, the potential market for a bird-repellent compound is relatively small, and the lack of potential sales plus the upfront outlay of funds necessary to obtain the registration combine to discourage economic development of these types of chemicals. There is, therefore, little variety in the chemical bird repellents that are available for agricultural uses. As a result, management options for growers are limited, and in fact for many crops, no repellent is available. The future development of repellent chemicals for crop protection probably lies in expanding the few labels that do exist to cover additional use patterns, rather than registration of new repellent compounds.

BIRD-REPELLENT COMPOUNDS

Methyl anthranilate (MA) is a naturally occurring compound that is used extensively in the food industry to impart grape or fruity flavor to candy, gum, soft drinks, and other consumables. As such, it is one of a number of compounds generally regarded as safe (GRAS-listed) by the U.S. Food and Drug Administration. Even though MA is palatable to humans, it is an irritant to birds. The bird-repellent properties of MA and related compounds were discovered in the late 1950s (25). The mode of action is via the trigeminal nerve. Thus, all avian species tested so far perceive MA as an irritant, not as a taste repellent per se. The repellency and mode of action of MA have been demonstrated experimentally through behavioral trials with intact and nerve-cut birds (26). Birds consistently reject food and water treated with MA at the appropriate level. This is a reflex response that does

Table 1. Compounds Recently Identified with Bird-Repellent Properties

Compound	Principal Species Tested	References
Cinnamamide	Rock dove, Rook, Chaffinch	72,73
Coniferyl benzoate	Ruffed grouse, European starling	74,75
Cucurbitacin	Red-winged blackbird	56
Imidacloprid	Red-winged blackbird, Brown-headed cowbird	76,77
Methyl cinnamate	Red-winged blackbird	78
Ortho-aminoacetophenone	European starling	65,79
Pulegone	European starling, Red-winged blackbird	80,81

not have to be learned. Rejection of tainted food varies, however, according to the motivational state of the bird. With no alternative food, or with a relatively unattractive alternative food available, birds will persist and eat the MA-treated food. If, however, MA-treated food is offered with the same food type available, but untreated, rejection of treated food occurs at much lower treatment levels (27). Because the irritation caused by MA may not be a very strong aversive stimulus, birds tend to return and test the treated food so that loss can accumulate even though the repellent is in place. The strong grapelike odor of MA is not aversive to birds (28). Birds have to contact the MA-treated food with their mouths in order to feel the effects of the compound.

In the United States, MA is the active ingredient in various formulated products marketed under the trade names of Bird Shield and ReJeX-iT. These products are registered as bird repellents for use on cherries, blueberries, and grapes. In addition, other formulations are registered for use on turf and water to control geese and other grazing birds. (Information obtained from web sites, *www.bsrc.com* and *www.nei2000.com*, as of 1 December 1999.)

In using MA-based formulations, it is important to keep in mind several characteristics of MA. 1) This is a volatile compound that dissipates rapidly. The rapid dissipation is exacerbated by degradation due to ultraviolet radiation and due to microbial activity (24). To some extent, the life of the treatment can be extended through encapsulation of the active ingredient and incorporation of ultraviolet protectors and anti-microbial agents in the formulation. 2) Rapid dissipation or degradation of MA can be a mixed blessing. Even though the effectiveness of the treatment will not persist very long, rapid loss of the compound will remove the grapelike flavor of MA so that the taste of the picked fruit is not tainted. The prevention of flavoring of fruit for fresh markets is especially important as these commodities are not washed after picking. The fruit goes directly into containers for shipping to stores. 3) The volatility and reactivity of MA can cause phytotoxic effects on sprayed vegetation (29). Appropriate formulation can ameliorate this problem; so in most cases phytotoxicity of MA should not be a concern.

Controlled field evaluations of the efficacy of MA as a bird repellent on fruit crops are few. In New York, bird damage to MA-treated blueberry plots did not differ from that in untreated plots (30). There was, however, some reduction in damage achieved in test plots in grapes and cherries. A large-scale field trial at several sites in Michigan, Oregon, and Washington did not demonstrate reduced bird use of MA-treated blueberry plots (31). Recent field trials suggest that aerial application of MA to corn and sunflower can discourage depredations by flocks of blackbirds (32).

When applied to grass, turf, and winter wheat MA reduces grazing by geese and other species at golf courses, parks, and crop fields (33,34). Furthermore, the uses of MA continue to expand. In addition to the turf crop and turf applications, the current registered uses include fogging the compound to disperse nuisance roosts and flocks of birds at airports, applying it to landfills to reduce the numbers of gulls and other bird species, and treating temporary pools and non–fish-bearing bodies of water to discourage use by waterfowl around airports and residential communities. Recent experiments suggest that MA could possibly be used as a secondary repellent (35). The challenge is to encapsulate the MA so that birds ingest it without feeling pain or irritation. Once the repellent is in the gut, irritation by the chemical produces an emetic reaction leading to the formation of a learned avoidance response (35).

Anthraquinone

In the United States, the use of 9,10-anthraquinone as a bird repellent dates at least from the early 1940s when the first patent for this use was issued (36). Subsequent development and testing of the compound centered on seed treatments, particularly for pine seeds and for rice. Anthraquinone was not registered in the United States, but it was registered in Europe and continues to be used as a seed treatment there. In recent years, however, anthraquinone has resurfaced as a bird repellent in the United States under the brand name Flight Control, and it is now registered as a treatment to repel birds from turf and grass and as a repellent for roosting birds. Additional bird-repellent applications for athraquinone are being developed, including rice and corn seed treatments (37), and aerial application to ripening rice (38,39).

Anthraquinone is a secondary repellent and affects birds by causing post-ingestional distress (40). Sometimes, ingestion of anthraquinone-treated food produces vomiting, but often vomiting does not occur and the bird just sits quietly until the discomfort passes. Unlike methiocarb, anthraquinone doe not affect the bird's nervous system and does not immobilize affected birds. Presumably, the emetic response is produced through irritation of the gut lining, but the actual mechanism is unclear. It is clear, however, that anthraquinone is not a taste repellent or contact irritant. Birds do not hesitate to eat treated food, and they exhibit no sign that treated food is unpalatable to them. The post-ingestional discomfort that results from eating anthraquinone-treated food produces a conditioned aversion to that food type. Birds need to experience the adverse consequences before learning to avoid the protected food. Thus, it is not reasonable to expect losses to cease immediately upon application of the repellent. There will be some level of loss in the crop as the depredating birds acquire the learned avoidance response.

Anthraquinone is a stable compound that is virtually insoluble in water. It is not phytotoxic and does not inhibit germination of rice seeds or growth of sprouts. It has very low toxicity to birds and mammals, and it appears to be innocuous to insects as well. There is no known hazard to nontarget species from repellent applications of Flight Control.

Another potential aspect to the effectiveness of Flight Control as a bird repellent is the fact that its reflectance spectrum peaks in the near-ultraviolet wavelengths. This part of the spectrum is also where the visual sensitivity of bird species such as the red-winged blackbird is maximal (41). What, if any, role ultraviolet reflectance plays in the repellent nature of Flight Control is conjectural. Possibly, the ultraviolet reflectance enhances the bird's ability to associate the appearance of treated food with the adverse post-ingestional consequences and thereby learn more rapidly to avoid the treated food.

Methiocarb (3,5-dimethyl-4-[methylthio]phenyl methylcarbamate)

This compound was originally developed by Bayer as an insecticide. The bird-repellent properties of the compound were quickly recognized, however, and a number of applications for bird damage management followed (42). Methiocarb is a carbamate, and its mode of action is via the inhibition of acetylcholinesterase at synapses in the nervous system. Unlike many cholinesterase-inhibiting compounds, however, the effects of methiocarb are rapidly reversible, and the animal experiences only transitory disruption. Affected birds exhibit a range of symptoms, including retching, vomiting, and temporary paralysis. The time to onset of symptoms, and the severity of those symptoms, is dependent on the dose received. Typically, vomiting begins within 10 minutes of ingestion of treated food. An affected bird can become immobilized within 30 minutes of ingesting an appropriate dose, and it will recover fully in another 30 minutes. Birds that feed on methiocarb-treated food exhibit no sign that the chemical tastes bad. Treated food is readily accepted, and feeding slows only when the bird begins to detect physiological effects of the chemical.

Methiocarb is a secondary repellent, and repellency occurs through aversive conditioning, by which birds that feed on treated food become sick and associate either the food or characteristics of the food with the discomfort (21). As a result, affected birds learn to avoid that food item. Often the avoidance response is location-dependent. For example, common ravens (*Corvus corax*) that learn not to eat eggs at one site will still feed on eggs at a different location (43). The avoidance response is also affected by various other factors such as the bird's prior experience with the food item, the strength of the post-ingestional discomfort, and the availability of alternative food. Anthraquinone would likely be similar in these respects.

Methiocarb is classified as "extremely toxic" because of its low acute oral rat median lethal dose (LD_{50}), 15–35 mg/kg (44). This is important for human health and safety, but it is misleading when considering the effects to birds. Applied properly, methiocarb is very safe with regard to target and nontarget species (45). Although the LD_{50} is low, free-feeding birds acquire a repellent dose and stop feeding long before a lethal dose is ingested.

In North America, methiocarb has been tested extensively in many agricultural applications. It has been used to protect newly seeded and sprouted crops, ripening grain crops, and soft fruits. It was commercially sold as Mesurol and for several years was registered in the United States as a bird repellent on cherries, grapes, and blueberries and as a treatment for corn seed. The registrations lapsed in 1989, however, when the registrant declined to meet additional data requirements specified by the U.S. Environmental Protection Agency. In the United States, methiocarb is now used as a molluscicide on ornamental plants. Methiocarb is registered as a bird-repellent seed treatment for rice in Uruguay, where the product is known as Draza. The rights to methiocarb were recently acquired from Bayer by Gowan Company (Yuma, AZ). Despite the company's interest in methiocarb as a bird repellent, the outlook for obtaining agricultural registrations in the United States is bleak given the current regulatory climate and increasingly strict laws protecting human health, such as the 1996 Food Quality Protection Act. Methiocarb has also proved effective as a bird repellent to deter grazing by geese on turf (46) and is as a nonlethal means to reduce avian predation on eggs of endangered species (43) labeled with the USEPA.

Avitrol (4-aminopyridine)

Avitrol is considered by some to be a "behavioral repellent." It is highly toxic to birds and mammals. In the United States, there are several registrations for the control of blackbirds, pigeons, and various other bird species. Avitrol repels birds by poisoning some members of the feeding flock, causing them to become agitated and hyperactive. The distress calls emitted by the fatally poisoned birds frighten the other members of the flock so that they leave the area. Presumably, after one such experience, the birds do not return to the site. In experimental evaluations of Avitrol in corn and sunflower fields, however, the compound has not proven consistently effective (47,48).

Fungicides

Although not designed to be used as bird repellents, a number of fungicides have been shown to reduce feeding activity of various bird species. Thiram (tetramethylthiuram disulfide) is used as a seed treatment. The chemical depresses central nervous system activity but has low oral toxicity (43). There have been several studies that have documented the repellency of thiram to birds (49,50). Ziram (zinc bis[dimethyldithiocarbamate]) has shown potential usefulness as a repellent to protect orchids and other valuable flowers (51).

Several copper compounds are used widely as fungicides, and at least two of them, copper oxychloride and copper hydroxide, have been tested for bird repellency (50,52). Each of these compounds reduced consumption of treated food. Copper ingestion can lead to post-ingestional distress, and these compounds probably act as secondary repellents by irritation of the gut lining, although the mode of action is not clear.

Panoctine (guazitine triacetate) is used widely throughout the world as a seed treatment, but it is not available in North America. Where it is used, Panoctine is considered a repellent to various bird species. Feeding trials with captive red-winged blackbirds demonstrated repellency in choice tests but not in tests where birds had no source of untreated alternative food (50).

Other Compounds

Several substances that have offensive properties to humans are marketed as bird repellents. RoPel is marketed as a spray and in granular form as a repellent for geese, ducks, and woodpeckers on lawns and around structures. The active ingredients are denatonium saccharide and thymol, neither of which is known to be particularly offensive to birds. Bye-Bye Birdie is sold in granular form as a repellent to deter starlings, pigeons, sparrows, and other birds from structures. It contains 100% naphthalene, which has been shown to be inoffensive to birds (53,54). In Australia, Duck Off is used as a turf treatment sprayed to deter ducks and other species from golf courses and other areas. The active ingredient is aluminum ammonium sulfate, a very astringent compound. Previously, this compound, synergized with sucrose octa-acetate, was sold as a bird repellent in the U.K. as Curb. Field trials of the same compound in Africa showed that it protected ripening cereal grains for several weeks from depredating flocks of birds (55). At least some bird species are sensitive to bitter compounds (56), so it certainly is possible bitter or astringent compounds can be formulated to produce safe, effective bird repellents.

There is a persistent impression that capsaicin, the active principle in hot capsicum peppers, is an effective bird repellent. Various products are routinely marketed to deter birds from crops, structures, and for other uses. This is despite the fact that there is well-documented evidence that birds are relatively insensitive to capsaicin, and in fact, seeds of capsicum peppers are dispersed by birds (57). There are fundamental differences between the avian and mammalian chemosensory worlds, and just because a compound is irritating or offensive to mammals does not mean that birds will respond similarly (58).

There is evidence that derivatives of the neem plant (*Azadirachta indica*) have bird-repellent properties (59,60). Recent studies suggest that the degree of avian repellency of neem compounds is determined by the concentration of azadirachtin (61), a compound that inhibits insect growth and development.

Lindane (Isotox), an organochlorine compound, was formerly used as a seed treatment. It is no longer manufactured in the United States, and most agriculture uses have been canceled by the U.S. Environmental Protection Agency because it is considered a potential carcinogen.

REPELLENTS TO REDUCE INGESTION OF GRANULAR PESTICIDES

As a normal part of their dietary habits, birds regularly ingest small particles of grit that serve to grind hard food items in the birds's gizzard. Grit ingestion has become an important topic in recent years because birds sometimes ingest granular pesticides as they search for grit particles. Many of the granular pesticides are very toxic, and as a result of accidental ingestion by birds, there have been a number of documented bird kills. Many aspects of the granular particle, such as size, shape, texture, and color, can potentially be manipulated to make the granular less appealing or less likely to be taken by a foraging bird (62,63).

A potentially useful application of an aversive primary repellent is as a constituent of granular pesticide formulations (64). Because many granular pesticides are very toxic, birds cannot afford to learn to avoid the granules. Thus, a secondary repellent is not appropriate. Primary repellent chemicals may be useful, however, provided such a repellent will be sufficiently irritating to cause a bird to drop the granule immediately. Methyl anthranilate might be a candidate for such a use, but ideally to ensure that the toxic granule is not ingested, a more aversive compound should be sought. Other compounds more aversive than MA have been identified (65), but definitive tests of whether these materials would actually reduce granule ingestion by birds have yet to be performed. Furthermore, compatibility of the repellent with the pesticide formulation would have to be determined.

SUMMARY AND FUTURE DEVELOPMENTS

Although there are numerous potential applications for avian repellents, such compounds are not the answer to every crop damage situation. Understanding the specifics of bird-crop interaction is essential to successful use of chemical bird repellents. This is illustrated by the situation in northern California where blackbird damage to wild rice is an ongoing concern. Blackbirds consume seed during the milk, dough, and mature stages, and further damage results from bird movements within the crop that causes seed heads in the mature stage to shatter. Estimated losses range from $121 to $309/ha (66). Control of damage relies on the use of frightening techniques (shotguns, propane cannons, etc.), which have only limited effectiveness. When the bird-repellent Flight Control was applied to ripening plots of wild rice, there was no observed effect on the blackbirds feeding in those plots despite the fact that similar rates of application did reduce blackbird numbers in plots of ripening white rice in Louisiana (67). This result was surprising until it became clear that blackbirds were doing more in the wild rice than just feeding. Blackbirds use wild rice crops for loafing and escape cover, as nighttime roosts, and for nest sites. Thus, unlike fields of white rice, wild rice provides the same resources to blackbirds as their natural habitats. By applying a feeding deterrent, we did not address the other reasons for the birds being there, thus, had little impact on the birds' activity. The deficiency was not in the repellent, but in the way in which it was used.

Even the most successful repellent will not eliminate damage by birds. The only way to accomplish that is to employ netting or some other means of exclusion, an option that in most cases is not economical or practical. Repellents are tools or methods that are best viewed as components of integrated management plans, rather than as solutions by themselves. By combining techniques, it is possible to attack many sensory modalities at once and thereby increase the likelihood of creating an uncomfortable foraging environment for the depredating birds. The effectiveness of various combinations of methods for bird damage management is an area of research that is largely unexplored.

In a similar vein, a promising area of future research is the investigation of various combinations of repellents themselves. Using mixtures of primary repellents and secondary repellents with a color as a visual deterrent creates opportunities for improved repellency with less-active compound used (67,68).

Although many naturally occurring compounds are avian feeding deterrents (6,69), few of these have been evaluated as potential repellents for agricultural use. There is a vast amount of information on chemical ecology and interactions between arthropods and avian predators that could potentially be applied to crop protection. This field is ripe for research and may result in new, improved repellents of the future, although just because a compound occurs naturally is no assurance that it is safe (18).

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