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Abstract: Several species of cranes and other wildlife have recovered from low populations because, in part, they have adapted to resources found in agricultural environments. If future conservation strategies are to succeed in areas dominated by agricultural use, we must develop sustainable models that solve crop damage problems that are caused by expanding wildlife populations. Using crane damage to planted seed as an example, we propose 1 such model of sustainable crop damage prevention. The deterrent, 9,10-anthraquinone (AQ), is a natural product produced by plants, in part to control bird frugivory, and induces gastro-intestinal distress (temporarily sickens an individual) in sandhill cranes (*Grus canadensis*) as well as other bird species. AQ is an effective deterrent because it induces a physiological response at first and is then accompanied by a conditioned avoidance. Yet, AQ is not toxic to birds nor are birds likely to habituate to the deterrent. Seed repellents cause birds to avoid treated foods among several possible items found within the same field. Other, more traditional, crop damage repellents (e.g., propane cannons) operate by moving birds among fields within home ranges. Excluding preferred habitats such as cornfields increases the risk that birds will habituate to deployed damage solutions. AQ products have adapted to a diverse farm environment and cost less than 3% of total planting costs. They were applied to prevent crane damage on planted corn for more than 67,000 ha in the Midwest during 2018 and can be deployed at whatever spatial scale that damage severity warrants. Our model using AQ as a seed treatment to prevent crane damage to germinating corn has been applied to pheasants (*Phasianus colchicus*) and blackbirds (Icteridae) as well as in rice and sunflower crops. As such, this model presents a sustainable approach that arises from solutions that allow agriculture and wildlife to co-exist.

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The recovery of the Eastern Population (EP) of greater sandhill crane (*Grus canadensis tabida*) from near extirpation to widespread abundance is a wildlife success story (Lacy et al. 2015). For this story to remain positive, management strategies must refocus from population recovery to mitigating problems inherent with population abundance. Many crane species, as well as other wildlife, have recovered in a similar manner because they have adapted to using resources that are now found in agricultural fields (Nowald et al. 2018). In the Midwest, the highest densities of breeding cranes occur where wetlands and agricultural areas intersperse (Su et al. 2004, Lacy et al. 2015) and sandhill cranes use agricultural areas extensively on breeding areas (Su 2003, Miller and Barzen 2016). Crane consumption of planted corn seed, however, causes significant damage to cornfields (Lacy et al. 2013), and the problem is dependent upon the density of crane populations (Barzen et al. 2018). Damage that cranes cause to planted seed has been documented widely in Wisconsin (Bennett 1978, Melvin 1978, Barzen and Ballinger 2017). Scenarios that parallel Wisconsin exist in other nesting areas of the EP and in other crane species as well (Austin et al. 2018). Successful management of recovering crane populations will require effective and efficient solutions that can be deployed over large geographic areas wherever crane densities are high enough to cause significant damage.

Current established techniques that have been implemented to stop consumption of planted seeds have largely failed. For example, cranes habituate to propane cannons, no matter how cleverly deployed in cornfields, because individual cranes quickly habituate to the disturbance and because cornfields are highly preferred by cranes (Barzen and Ballinger 2017). Lure crops and artificial feeding can abate damage in surrounding production fields but often attract more birds and eventually cause damage to resume as increasing bird use outstrips resources provided (Nowald et al. 2018). Though hunting, in combination with other techniques, has reduced crane damage in autumn (Austin 2012, Austin and Sundar 2018), fall hunting is unlikely to deter spring damage unless it lowers crane population levels dramatically, a condition that is unlikely to receive public

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support (Barzen and Ballinger 2017). In contrast, seed treatments have proven effective at preventing damage to planted seed for a variety of bird species (Werner and Avery 2017), and for sandhill cranes specifically, through use of 9,10-Anthraquinone (AQ; Blackwell et al. 2001, Barzen et al. 2018, Lacy et al. 2018).

From the collective perspective of growers, regulators, ecologists, agronomists, and consumers, any successful deterrent must: 1) effectively prevent bird consumption of planted seeds, 2) protect planted seeds while they retain endosperm (food for birds), 3) break down in soil following the seed's vulnerable period, 4) be environmentally safe, 5) incorporate easily into current agricultural system, 6) be widely available, and 7) be economical to use. Meeting the needs of end users is critical to crane management because most land in the U.S. is privately owned (U.S. Census Bureau 1991:201), and of privately owned land, a majority of land is used for agriculture (Nickerson et al. 2011). Because agriculture provides much of the habitat preferred by cranes in the EP, effective collaboration with growers is needed for the long-term success of crane management. This is likely true with cranes worldwide (Austin et al. 2018, Nowald et al. 2018). Without such collaboration, agricultural techniques will likely evolve independently of wildlife needs (e.g., increase harvesting efficiency) and could become detrimental to cranes or other wildlife as is happening in cornfields adjacent to the Platte River (Krapu et al. 2004).

For collaborations with these stakeholders to be successful, our challenge as conservationists is to meet crane and grower needs simultaneously (Barzen 2018). The goal of this paper is to present a model of sustainable crop damage deterrence that works for seeded crops. Specifically, we will 1) identify the origin of the interaction between plants that use AQ and animals, 2) summarize the mechanisms of deterrence in cranes, 3) discuss applications of this method to other bird species and crops, and 4) outline an ecological, as well as agricultural, context for sustainable solutions to crop damage.

ORIGIN OF THE RELATIONSHIP BETWEEN PLANTS THAT CONTAIN AQ, HERBIVORES, AND HUMAN TOXICITY

Anthraquinones are ubiquitous in the plant world (DeLiberto and Werner 2016). As a class, the compounds mediate biotic and abiotic interactions with the environment (DeLiberto and Werner 2016). The molecular structure of AQ, for example, acts as a redox catalyst and is a part of the photosynthetic cycle (Korulkin and Muzychkina 2014). Plants commonly have secondary uses for molecules and AQ provides a well-known example. Some plants express variable concentrations of AQ during the fruit maturation process to aid in seed dispersal (Korulkin and Muzychkina 2014) such that high concentrations of AQ occur in unripe fruit and are thought to deter birds from consuming it (Sherburne 1972). Once ripe, AQ concentration in the fruit is reduced and birds consume the fruit, dispersing the now viable seeds (Sherburne 1972, Werner and Avery 2017). Some insects also concentrate various anthraquinones in their bodies that are obtained from plant sources (Hilker and Kopf 1994). AQ concentrations in invertebrates deterred predation by ants (Hilker 1992) and, in a manner similar to cranes, AQ concentrations in insects reduced bird predation through altering learned foraging behavior in tits (*Parus major* and *P. ater*; Hilker and Kopf 1994). In some cases, insects even produce these compounds through a symbiotic process with flora in their gut. Anthraquinone derivatives are also found in lichen and are both antibacterial and antifungal (Korulkin and Muzychkina 2014).

A wide variety of medicinal uses for anthraquinones exist. Flavinoids and anthraquinones have been researched extensively over the last 40 years in search of unique uses in modern medicines and are found to influence a wide variety of diseases (Dave and Ledwani 2012). Food supplements take advantage of bioactivity in the anthraquinone family by including AQ compounds in products derived from *Senna*, noni (*Morinda*), *Rubia*, *Digitalis*, *Cassia*, and a number of tropical plants (Dave and Ledwani 2012). The original documented use of AQ compounds were as vegetable dyes extracted from the roots and leaves of various plants. The use of these dyes is traced back to several early civilizations around the Mediterranean and is found in a wide variety of plant species (Caro et al. 2012). Collectively this experience by humans with the AQ molecule suggests that the AQ compound is not likely toxic to humans nor environmentally persistent. AQ is not toxic to birds (Schafer 1972). Today, the compound that is used as a bird repellent is the parent compound of the anthraquinone family and has the useful characteristics of being insoluble in water, stable in sunlight (Arkion Life Sciences LLC, unpublished data), and yet is biodegradable in soil, leaving no residues of concern (Lacy et al. 2018).

Given such high potential exposure between AQ and animals, in particular people, it was surprising when early tests found AQ to be mutagenic and carcinogenic (National Toxicology Program 1999). Upon further examination of materials tested by the National Toxicology Program, however, the tested AQ was derived from anthracene (i.e., coal tar) and contained impurities at high enough concentrations to cause both the mutagenic and carcinogenic response seen in mice (Butterworth et al. 2001, 2004). Current industrial-produced AQ does not use anthracene as a base and relies on a different formulation process (Friedel-Crafts reaction) that produces nearly pure AQ, containing only small amounts of 1 impurity, 2 methyl anthraquinone, which is not mutagenic or carcinogenic (Arkion Life Sciences LLC, unpublished data). Arkion also discovered that AQ is an effective rodent repellent and re-examined the National Toxicology Program study to confirm that starvation effects confounded the results and contributed to outcome of that test on mice and rats.

After a full risk assessment analysis, the Environmental Protection Agency has re-issued the label for AQ on turf as a goose repellent (U.S. Environmental Protection Agency 2016) and issued a new seed treatment nationwide label for rice seed (U.S. Environmental Protection Agency 2017). Use of AQ on planted corn seed is currently used in 30 states under Section 24(c), Special Local Need Registrations of the Food Quality Protection Act, within each state. A nationwide label for AQ use on planted corn is expected soon. Use of AQ in Europe is not allowed because of the original findings of the National Toxicology Program study. The costs of re-evaluating use of AQ in Europe, given recent studies that reverse the conclusions of the National Toxicology Program study on AQ, are prohibitive without support from organizations within the European Union.

Arkion Life Sciences LLC, in cooperation with the USDA National Wildlife Research Center, continues to develop the AQ-based bird and rodent repellents. Currently, no other active substance has been found to replace AQ even though numerous other molecules, including existing fungicides and pesticides, have been tested since the early 20th century (DeLiberto and Werner 2016; Werner and Avery 2017; National Wildlife Research Archive, Fort Collins, Colorado, USA).

With no alternative currently known, understanding the interactions between plant production of AQ and bird herbivory is important to assessing the long-term viability of AQ as an effective deterrent. The co-evolution of birds and fruit-bearing plants suggests that it is unlikely that birds will habituate to AQ quickly. A way to assess the probability that birds will habituate to AQ is to evaluate the physiological, behavioral, and ecological mechanisms of AQ's deterrence. Physiological mechanisms such as pre-ingestive aversion (i.e., it tastes bad) versus post-ingestive distress (i.e., it makes an individual sick) that is coupled with conditioned (i.e., learned) avoidance, will moderate the adaptive ability of birds (Werner and Clark 2003). Behavioral and ecological mechanisms, in turn, may influence food availability and long-term bird response.

HOW AQ DETERRENCE WORKS IN CRANES

Protecting crops in a sustainable manner, while doing no harm to birds, has been our objective for 20 years. In 1998, what is now Arkion Life Sciences LLC (Arkion) and the International Crane Foundation (ICF) began collaborating in both field and captive bird studies that focused upon preventing crop damage by sandhill cranes. The collaboration also included U.S. Geological Survey's Patuxent Wildlife Research Center (PWRC), the U.S. Department of Agriculture (USDA), and the Wisconsin Department of Natural Resources (WIDNR). Taste tests with captive sandhill cranes were conducted at both PWRC and ICF by USDA researchers and ICF staff (Blackwell et al. 2001). In addition to a captive population of sandhill cranes, ICF had an established study area populated with wild, color-marked cranes where field trials with AQ could be conducted (Lacy et al. 2015, Barzen et al. 2018, Lacy et al. 2018).

Both lindane (Neff and Meanley 1956, Blus et al. 1984) and diazinon (Schafer et al. 1983) were identified as effective deterrents to bird damage on planted seed, and farm producers in our study area observed that a seed treatment containing both substances reduced crane damage. Neither lindane nor diazinon, however, was environmentally desirable. Lindane is no longer available for use on corn seed (U.S. Environmental Protection Agency 2006); it persists in the environment (Cheah et al., 1998), is resistant to photolysis and hydrolysis (except at high pH), and degrades very slowly by microbial actions (Walker et al. 1999). Diazinon now has limited use only (U.S. Environmental Protection

Agency 2007). From 1997 to 2001, ICF worked with farm producers to examine how crane deterrence caused by lindane and diazinon worked while we also searched for new deterrents that would be environmentally, agronomically, and economically acceptable.

In the early stages of field trials we tested 3 new deterrents: AQ, methyl anthranilate, and limonene, but only AQ showed promise for replacing lindane as being environmentally acceptable and physiologically effective (Blackwell et al. 2001, Barzen et al. 2018, Lacy et al. 2018). Both methyl anthranilate and limonene degraded too quickly in the soil to provide any effective deterrence (Lacy et al. 2018). Economic assessments for AQ had not yet been completed. Collectively, captive and field trials with AQ were the only successful trials and suggested that effective deterrence resulted from a complicated interaction of physiological, behavioral, and ecological processes.

Physiological Mechanisms

Unlike pre-ingestive repellents that depend on the trigeminal nerve response in birds, AQ functions through learned behavior stimulated by post-ingestive response (Avery et al. 1997, 1998). The physiological, post-ingestive response does not cause death or noticeable injury, but it does cause an immediate refusal of eating treated food (Werner et al. 2009). Tested birds have the ability to detect AQ through taste, sight, or smell, and they learn food avoidance after they associate pre-ingestive cues with the post-ingestive effect of AQ-treated food (Werner et al. 2008, Werner et al. 2009, Werner and Provenza 2011, Werner et al. 2014). Post-ingestive repellents, coupled with learned behavior, are thought to produce longer-lasting repellency because conditional training is based on important physiological responses as opposed to simple taste aversion (Werner and Provenza 2011). Pre-ingestive repellents were effective in novel exposures but soon lost their effectiveness as birds habituated to them (Werner and Clark 2003). The combination of post-ingestive deterrent and strong pre-ingestive cues is powerful enough to promote avoidance with low chances for habituation. With cranes this means that, after a few encounters with treated seed, cranes learn to avoid the post-ingestive repellent (Barzen et al. 2018).

Seeds detected underground by foraging birds are not found using visual cues but are likely detected by taste or smell. Captive cranes, upon tasting corn seed treated with AQ, immediately spit out the seed by vigorously shaking their head (International Crane Foundation, unpublished data). Memory of taste or smell can last several years in cranes (Barzen et al. 2018). AQ, however, is not absorbed by any part of the developing plant (M. Braverman, Rutgers University, unpublished data) so the only AQ encountered by foraging cranes is on the seed coat. Visual cues include the ability of AQ to absorb ultraviolet light (Arkion Life Sciences LLC, unpublished data). After geese sample a few treated seedlings they likely see the treated plants and avoid contact with them (Devers et al. 1998). Geese in flight, for example, have been observed diverting flight patterns in relation to AQ-treated turf so as to avoid landing on it (Arkion Life Sciences LLC, unpublished data). Geese have also differentiated treated from untreated turf, without consuming plants, under a light covering of snow. Ultraviolet light is known to penetrate light snow cover and it is interesting to speculate if the geese can determine where to find tender grass even under snow cover (Devers et al. 1998). Aerial-seeded rice fields can also benefit from ultraviolet cues that may help to prevent seed consumption by blackbirds.

Behavioral Mechanisms

Sandhill cranes are intelligent, territorial, long-lived birds that are highly philopatric (Hayes 2015). Sandhill cranes become sexually mature and capable of establishing a territory at 2 years old, a prerequisite of nesting successfully (Hayes and Barzen 2016). In crane populations at carrying capacity (Barzen et al. 2016), acquiring a territory often does not occur until a crane is >4 years old (Hayes 2015). Before establishing a territory, however, all non-territorial cranes in summer areas associate with each other in flocks that range from 2 to 100 individuals (Hayes and Barzen 2006). In Wisconsin, 2 social groups of cranes thus co-inhabit summer areas: territorial birds with small home ranges that average 2.8 km^2 (Miller and Barzen 2016) and non-territorial birds, whose large home range averages 28-197 km^2, depending upon the age of the bird (Hayes and Barzen 2016). Territories do not overlap significantly and persist among years (Hayes 2015), whereas non-territorial cranes select overlapping home ranges that contain diverse habitats and are used in a highly variable manner. Non-territorial birds also account for about 1/3 of the overall summer population of cranes (McKinney et al. 2016). Each social group, therefore, has different habitat use behavior that constrains it.

Ideal habitats for EP cranes in summer include a mixture of shallow, emergent wetlands that are located near upland areas (Su 2003, Miller and Barzen 2016). Though both non-territorial and territorial birds forage in uplands dominated by short (<0.5 m) vegetation and wetlands during the day, territorial birds typically feed in uplands that are adjacent to their nesting wetlands (Miller and Barzen 2016) while non-territorial birds forage in uplands that average 1.2 km from the nearest night roosts. Often cornfields that are used by non-territorial cranes in summer can be located up to 4 or 5 km from roosting wetlands (Su 2003).

While in upland fields cranes feed on seeds such as corn left over from the previous year's crop, larval insects, earthworms, and planted seeds as well as adult insects or vertebrates that are adventitiously acquired above the ground (Barzen et al. 2018). As a seed, corn is a desirable food for cranes as is wheat, barley, rice, and sunflower. Though exceptions occur (Lovvorn and Kirkpatrick 1976, Jha and McKinley 2014), soybean fields are usually undesirable to cranes (Krapu et al. 2004). While in cornfields or other open habitats, cranes are also relatively safe from predators and the open space provides a place for socialization such as mate selection, an activity that is especially important to non-territorial individuals.

In combination, behavioral characteristics and habitat needs of sandhill cranes create the potential for conflict between competing interests of farm production and bird conservation. If these conflicts can be resolved, growers are often willing to provide for crane habitat while they also grow their crops. In particular, recognizing which social group of cranes (territorial vs. non-territorial) is causing the most damage can increase the effectiveness of a deployed solution.

Planted cornfields present a simple array of food for foraging cranes because seed corn is planted in straight rows at constant intervals. Cranes, who efficiently probe for food in loose soil, and return to the same summer area each year, soon learn that planted fields offer edible foods in a predictable array that individuals can exploit. Planted seeds remain vulnerable to crane consumption until the endosperm is completely metabolized, no more than 17 days following germination (Lacy et al. 2018). While observing marked cranes foraging in AQ-treated cornfields, birds that sample planted kernels in treated rows reject kernels (Barzen et al. 2018) as do captive cranes exposed to AQ (International Crane Foundation, unpublished data). These same birds, upon experiencing treated kernels, quickly moved to foraging between rows where treated kernels were not present, suggesting selection of specific food items occurred among many items that were available within the same field. Accumulative exposure of cranes to AQ appears to be minimal because of rapid aversion responses.

Consumption of untreated kernels can be extensive. On average, 478 corn kernels/crane/day are ingested in spring (Barzen et al. 2018). Some cranes will not feed in agricultural fields at all while other cranes will feed mostly on corn and little else, consuming up to 1,357 corn kernels/day (calculated from Barzen et al. 2018; 1,459 food items/day × 0.93 kernels/food item). Damage to planted corn can be extensive in some fields (Fig. 1).

Though usually dispersed in small flocks, characteristics of particular fields sometimes attract large flocks of mostly non-territorial cranes. A sandy field, for example, is easier to forage in than a clay field (Bennett 1978). Typically, during the peak of corn germination, there is more area of available, vulnerable corn than there are cranes to utilize vulnerable fields so non-territorial cranes remain dispersed. Following peak germination, however, when relatively few planted fields are vulnerable and cranes are conditioned to feeding on corn seed, dispersed cranes can quickly aggregate in 1 field and severely damage it within 1-3 days (Barzen et al. 2018).

Habitat Selection and other Ecological Mechanisms

Habitat selection and other behaviors also influence broader ecological patterns for crane use of treated and untreated fields. Once the kernel's endosperm is consumed by the plant, damage no longer occurs in the field because cranes do not feed on the seedlings themselves. Cranes, however, do not abandon use of the field once the endosperm is gone (Barzen et al. 2018) but tend to continue foraging in the field until the plants reach approximately 1 m tall (Su 2003). Tall vegetation causes cranes to abandon use of cornfields and seek other areas with lower vegetation in summer (i.e., yards, alfalfa, potato, or harvested grain fields). If cranes continue to use cornfields after kernels are no longer vulnerable, it is likely that cranes are seeking other resources (e.g., food or habitat structure) available there. Likewise, when cranes continue to forage within AQ-treated fields, but not on

A

B

Figure 1. Aerial (A) and ground (B) views of crane damage to a cornfield. Cranes are adept at finding portions of a field that are untreated. Note that within the untreated field the bare soil areas have virtually no sprouts and are found as far from the road as possible while relatively undamaged areas of the untreated section remain close to the road. Photos by Mike Sawyers (A) and Anne Lacy (B).

treated seed, other foods are available and are consumed (Barzen et al. 2018). Since a diet shift occurs normally for cranes as planted corn ages, deterrents only advance the timing in which diet shifts occur by 2-3 weeks within the same field (Barzen et al. 2018). Diet shifts within the same field, whether influenced by seed repellents or not, suggest that habitat selection occurs at the within-field spatial scale (*sensu* Johnson 1980). Removal of planted seeds from the cranes' diet does not appear to have broad energetic or nutritional ramifications for cranes because mortality rates in this population, for both territorial and non-territorial adults, are low (Wheeler et al. 2018).

In contrast to shifting selection between food items within a field (Johnson 1980), other deterrents move individuals from 1 field to the next and are defined at the among-fields spatial scale of habitat selection. As such, among-field habitat selection either removes all food and other resources within a field where the technique is applied through deterrents or it attracts individuals to targeted fields. For example, propane cannons and pyrotechnics are designed to scare cranes away from the target field but, if displaced birds respond by moving to another field, the damage is moved, not abated (Barzen and Ballinger 2017). With intelligent, long-lived, philopatric cranes there is also incentive for individuals to learn that scare tactics are not detrimental. Lure crops also work at among-field levels of habitat selection by concentrating cranes in specific areas, encouraging cranes to avoid fields that are sensitive to damage. The long-term effects of lure crops deployed near agricultural fields, where studied, have been difficult to sustain. In the Hula Valley of Israel, for example, artificial feeding of Eurasian cranes (*Grus grus*) has prevented damage to surrounding agricultural fields. Implementation of artificial feeding, however, has increased the numbers of staging and wintering birds at a faster rate than what could occur by population growth alone (Shanni et al. 2012). If provision of artificial food does not keep pace with increasing crane numbers, damage of surrounding agricultural fields resumes. In the Hula, increasing income from tourism has offset rising feeding costs. It is unclear, however, if future feeding costs will eventually outstrip income. The effectiveness of artificial feeding for cranes using summer areas has not been yet been evaluated.

To protect the crop, within-field deterrents such as AQ remove only 1 resource in the field (the planted seed) and allow cranes to continue using other resources that exist in the same field. In addition, cranes can more easily habituate to deterrents that promote behavioral aversion without physiological conditioning such as found with propane cannons (between-field) or pre-ingestive repellents (e.g. methyl anthranilate) that operate as within-field deterrents. If the habitat is highly selected, as germinating cornfields are for cranes, habituation that is not reinforced by conditioning will be weakened as birds learn to avoid or ignore the deterrent.

By conducting our field studies of seed treatments and habitat selection on a marked population of sandhill cranes for more than 2 decades, we examined the potential long-term effects caused by widespread use of AQ. Most farm producers in our 6,500-ha study area now use AQ to treat their corn and have done so for the last 10 years. Mortality rates of marked cranes that feed in cornfields do not differ from mortality rates of marked cranes that utilize other habitats in our study area (International Crane Foundation, unpublished data). Productivity of nesting cranes that use treated cornfields also did not differ from the productivity of cranes that do not use cornfields (International Crane Foundation, unpublished data). Planted corn does not appear to be a critical food for cranes in spring.

Collectively, the effectiveness of AQ in preventing damage to planted seed at the within-field spatial scale is supported by the physiological, behavioral, and ecological mechanisms through which it works. AQ produces a post-ingestive response that then conditions a behavioral aversion determined by sight, taste, or smell of treated food. Non-territorial cranes are most likely to damage planted corn because of their mobility and can quickly concentrate foraging on vulnerable fields. Cranes respond to AQ-treated fields by switching food items within the field (i.e., within-field spatial scale) but not by dispersing away from treated fields (i.e., between-field spatial scale). Widespread use of AQ-treated fields within the Briggsville study area, however, does not appear to reduce critical resources for the crane population. Use of AQ provides a new tool for preventing damage to planted seeds by cranes in multiple crops to which it will be difficult for cranes to habituate in the future.

APPLICATION OF DAMAGE PREVENTION MODEL TO OTHER AVIAN SPECIES AND CROPS

Historically, the search for effective avian repellents has led to an understanding that repellents would contribute to crop protection, but repellents were either not persistent enough, were habituated to, or acted at the wrong geographic scale of habitat selection to fully protect a crop (Werner and Avery 2017, Barzen et al. 2018). New AQ repellent formulations have been extensively tested and found to be persistent and to effectively promote bird deterrence without toxicity. AQ repellents have now been successfully tested on seeds of corn, rice, soybean, sunflower, millet, and sorghum (DeLiberto and Werner 2016).

Bird consumption of planted seed, such as corn, is a recognized cause of yield loss along bird migration routes such as the Mississippi Flyway. Species that have caused the most damage include sandhill cranes, ring-necked pheasants (*Phasianus colchicus*), red-winged blackbirds (*Agelaius phoeniceus*), common starlings (*Sturnus vulgaris*), brown-headed cowbirds (*Molothrus ater*), and common grackles (*Quiscalus quiscula*) (DeLiberto and Werner 2016). Threshold concentrations for AQ occur for most bird species that damage planted seeds in North America (Werner et al. 2009, DeLiberto and Werner 2016) but do not appear related to body mass (Table 1), so determining threshold levels for new species is unpredictable, requiring additional testing.

Our detailed study of response by sandhill cranes in the field can inform damage control issues related to other bird species. For example, blackbirds would be expected to respond to AQ-treated, planted rice seeds as do sandhill cranes with AQ-treated corn, provided that other resources in rice fields remain available. As important, successful prevention of damage from 1 wildlife species may improve landowner attitudes for the conservation of other wildlife species. Extensive use of AQ to control blackbird damage to planted rice seed in Louisiana, for example, appears to have encouraged landowners to be more accepting of whooping crane (*Grus americana*) reintroduction. Whooping cranes reintroduced to White Lake Wetlands Conservation Area in southwestern Louisiana began using rice fields north of the reintroduction area, especially when fields were flooded for rice or crawfish (*Procambarus* spp.) production (Pickens et al. 2017). Conversations with 1 author (JAB) suggested that some landowners were less wary of a new species using their fields since they had solved problems with blackbirds damaging planted rice.

ECONOMICS OF SUSTAINABLE CROP DAMAGE SOLUTIONS

In any given year, 1.1 million ha of Wisconsin corn is estimated to be located within 1.2 km of an emergent wetland that cranes might use for roosting (Lacy et al. 2013). Though every planted cornfield within these potentially vulnerable areas does not need to be treated, the scale of an effective solution is clearly large enough to be beyond the ability of any single organization or government agency, as currently configured, to deploy unilaterally. We argue that the extent of the problem also suggests that compensating growers for use of deterrents would be difficult, if not impossible, to support because funding mechanisms such as portions of hunting license fees or other types of government payment simply cannot generate enough funds to match the magnitude of the problem. Even if the cost for deterrence were $1.00/ha, the cost for deterrence statewide ($1.1 million) would be prohibitive. We believe that the use of AQ is sufficiently economical that farm producers will use and pay for AQ on their own.

Over the last 13 years, AQ has been deployed through the market place to prevent crane damage in Michigan, Minnesota, and Wisconsin (Fig. 2). Use of AQ steadily

Table 1. Threshold concentrations of anthraquinone applied to 3 agricultural seeds consumed by 5 bird species. Threshold concentration data are from Werner et al. (2009) and DeLiberto and Werner (2016).

Subject	Body mass (kg)	Seed	Threshold concentration anthraquinone (ppm)
Greater sandhill crane	4.5-5.5	Corn	2,500
Canada goose	4.3-4.8	Corn	1,450
Red-winged blackbird	0.05-0.08	Oil sunflower in hull	1,994
		Rice	5,000
Common grackle	0.09-0.12	Rice	20,000
Ring-necked pheasant	1.2-1.4	Oil sunflower in hull	15,800
		Corn	10,450

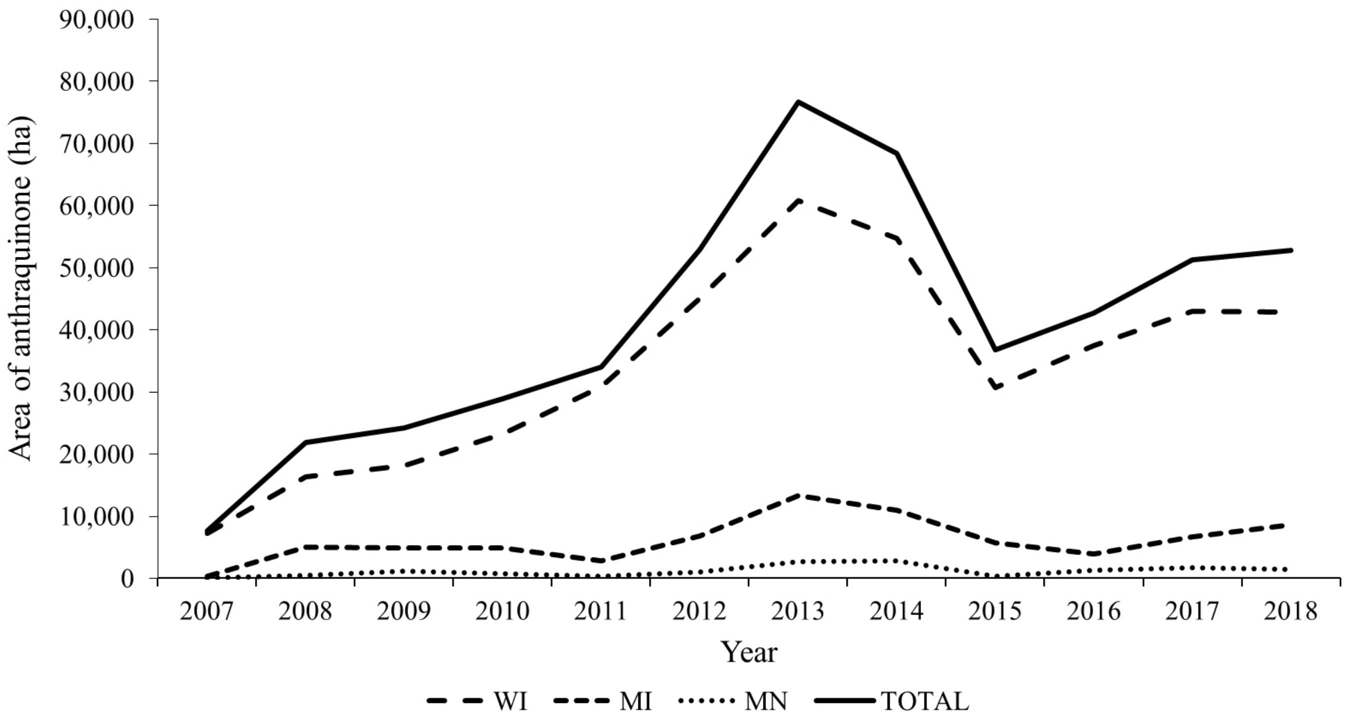

Figure 2. Area (ha) of planted corn treated with 9,10-Anthraquinone 2006-2018 in 3 states of the Midwest (Michigan, Minnesota, and Wisconsin).

increased in Wisconsin 2006-2013, after which use became more variable. Use of AQ in Wisconsin may now be on the rise again (Fig. 2). For 2017, 4% (43,008 ha) of the 1.1 million ha of potentially vulnerable fields in Wisconsin were treated with AQ. In Michigan and Minnesota, use of AQ was more erratic over the same period. Decisions related to treatment likely include the price of corn (thus the cost of planting) as well as the risk assessment growers might use to predict if cranes are likely to damage a particular field in any 1 year. Such risk assessment evaluations follow Integrated Pest Management guidelines and are desirable (Dent 1995). As data become more available, risk assessment will become easier. Importantly, over the last 13 years the commercial AQ deterrent (Avipel®) has been incrementally improved to accommodate diverse agricultural needs and environments. Formulations of powder and liquid have been altered to ensure that all seed is coated with threshold levels of AQ and that these coatings work in planters that vary from mechanical plate planters to computer-driven planters with delicate ocular sensors. Powder formulations can be used in hopper-box treatment that allow for last-minute planting decisions while liquid treatments allow for pre-order of large seed batches. Ease of use for this deterrent, in other words, has improved over a decade of effort, and this adds to the sustainability of the solution.

More generally, in any part of the country, growers treating entire fields of planted crop experience less than 1% crop loss from any bird species (Arkion Life Sciences LLC, unpublished data). Cost for this treatment varies by crop since the repellent is applied to seed by weight. In the upper Midwest, the cost of prevention for corn growers is about 3% the cost of planting. Where costs of prevention are economical, market forces can determine the scale at which preventative techniques will be used. Growers benefit from a tool that is effective, that works in their agricultural system, and that they have control over. The value of growers being able to independently solve wildlife problems that they encounter should not be ignored.

The model of deploying AQ as a deterrent to bird consumption of planted seeds through the marketplace is unique and holds great promise as a method for allowing wildlife to co-exist with the agricultural community on a sustainable basis—a proverbial win/win for conservation and agriculture. Further, solving the problem at the scale of selection that distinguishes among food items within the same field, coupled with the co-evolution of plants and birds regarding control of avian herbivory, offers the important likelihood that habituation to AQ by birds can be avoided. Deployment of the AQ deterrence model fits agricultural needs by 1) reducing bird damage to planted seeds to <1%, 2) persisting in the soil for 3-4 weeks, long enough to protect planted seeds while they retain endosperm, 3) being biodegradable in soil, 4) being non-toxic to birds, 5) working with all types of planters currently in use, 6) being legally available in 30 states and soon as a nationwide label, and 7) costing less than 3% of planting costs. As such, our model has potential for application to a number of bird species and crops. To extrapolate our model further (e.g., to insect damage on plants) requires substantial additional research but identifies the value of an ecological approach to plant/animal relationships.

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