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ESASeedPARAM: A seed treatment model for threatened and endangered bird species in the United States

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Abstract

The USEPA, National Marine Fisheries Service, and Fish and Wildlife Service are required to assess the risks of pesticides undergoing registration or reregistration to threatened and endangered (i.e., listed) species. Currently, the USEPA lacks a refined model to assess the risks of seed treatments to listed bird species. We developed the Endangered Species Assessment Seed Treatment Probabilistic Avian Risk Assessment Model (ESASeedPARAM) to incorporate species-specific diets, body weights, and food ingestion rates for potentially exposed listed bird species. The model also incorporates information on dissipation of seed residues after planting, and metabolism and elimination by birds during exposure. The ESASeedPARAM estimates hourly intake from ingestion of treated seeds for up to 50 days after planting. For each simulated bird, maximum retained dose (= body burden) and maximum rolling average total daily intake are estimated for acute and chronic exposure, respectively. The model is probabilistic and estimates exposure and risk for 20 birds on each of 1000 fields. The model accounts for interfield variation in the amount of waste grain on the soil surface in tilled, reduced till, and untilled fields. To estimate the fate of each bird from acute exposure, a random value is selected from the appropriate dose–response relationship and compared with the maximum retained dose. If acute exposure exceeds the randomly chosen effects value, mortality is assumed. For chronic risk, the most sensitive No Observed Adverse Effects Level (NOAEL) and Lowest Observed Adverse Effects Level (LOAEL) for an apical endpoint (survival, growth, reproduction) are compared with maximum rolling average total daily intake. In this article, we describe a case study conducted with the ESASeedPARAM for imidacloprid used as a seed treatment on wheat and soybean. *Integr Environ Assess Manag* 2023;19:527–546. © 2022 SETAC

KEYWORDS: Neonicotinoid; probabilistic model; seed treatment; threatened and endangered bird species

INTRODUCTION

Neonicotinoids, such as imidacloprid, clothianidin, and thiamethoxam, are frequently applied to seeds (i.e., seed treatments) before planting to control early season insect pests that reduce yield and destroy crops. Neonicotinoids have very low toxicity to mammals compared with many other pesticide classes including carbamates, organophosphates, and pyrethroids (Goulson, 2013; Sanchez-Bayo, 2011; Tomizawa & Casida, 2005). As a result, neonicotinoid seed treatment products have been widely adopted because of their efficacy, ease of use, and reduced risks for pesticide handlers (Douglas & Tooker, 2015). However, concerns have been raised regarding the risks posed by neonicotinoid seed treatment products to birds that forage on or near treated fields (Eng et al., 2019; Gibbons et al., 2014; Goulson, 2013, 2014; Lopez-Antia et al., 2015, 2016). Currently, species-specific models are not available to assess the risks of neonicotinoid and other seed treatments to birds including threatened and endangered bird species (i.e., listed bird species) in the USA. In this article, we describe a refined, species-specific model, the Endangered Species Assessment Seed Treatment Probabilistic Avian Risk Assessment Model (ESASeedPARAM), for assessing risks of seed treatments to potentially exposed listed bird species. The model is illustrated using imidacloprid as a case study of neonicotinoid seed treatment.

Currently in the USA and its territories (i.e., American Samoa, Guam, the Northern Mariana Islands, Puerto Rico, and the US Virgin Islands), there are approximately 100 listed bird species and populations of which approximately a third have designated critical habitats. In previous assessments for listed species, the USEPA only assessed the risks of neonicotinoids applied as foliar and ground sprays, not seed treatments (e.g., US Environmental Protection Agency [USEPA], 2021a, 2021b, 2021c). Assuming that off-field movement is not an issue for seed treatments (i.e., production of abraded dust is properly controlled), the major exposure route for listed bird species is direct consumption of treated seeds. Thus, only listed bird species that are

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granivores or omnivores with ranges that overlap crop footprints where treated seeds may be used are potentially at risk from this major exposure route.

There are nearly 40 listed bird species that consume seeds and grains as part of their diet. Of these, only a few have seeds and grains making up more than 25% of their diet. Some of the species that consume seeds and grains are unlikely to occur in areas where seed treatments may be used. For example, spectacled eiders spend most of their time in the Arctic Ocean and nest along the Alaskan and Siberian coasts (Petersen et al., 2020). Nevertheless, there are listed bird species that could consume treated seeds (e.g., whooping cranes may forage in soybean and corn fields during migration; Urbanek & Lewis, 2015).

This article begins by identifying those listed bird species that could consume treated seeds based on a review of the diets of listed bird species and their ranges relative to crop footprints that have seed treatment uses. Next, the refined, probabilistic seed treatment model for listed bird species is described. We then describe the input variables used to estimate exposure, effects and risk, and model outputs for a case study with imidacloprid used as a seed treatment in soybean and wheat. The Supporting Information has additional information on model input variables and the listed species included in the model.

LISTED BIRD SPECIES POTENTIALLY EXPOSED TO SEED TREATMENTS

The first step in developing the ESASeedPARAM was to determine which listed species to include in the model. We considered all listed and proposed bird species in the USA and its territories. Candidate bird species proposed for listing under the Endangered Species Act (ESA) have no statutory protections and thus were not considered.

A query of the US Fish and Wildlife Service's (US FWS) ECOS database (www.ecos.fws.gov) for listed bird species was performed on 9 June 2021. The query included all bird species listed as endangered, threatened, and proposed. The query returned 98 unique species and two listed populations, resulting in 100 unique listed entities. Using information from Supporting Information: Appendix C in the final Biological Opinion for malathion (US Fish and Wildlife Service [US FWS], 2022), 15 species were removed from consideration because they are extirpated or extinct from the USA and its territories or are only found on uninhabited, remote islands (Supporting Information: Table SI-1). One additional species, the Guam Micronesian kingfisher, was also removed because it is restricted to a captive breeding program, and no individuals currently exist in the wild (Supporting Information: Table SI-1).

The remaining 84 listed bird species and populations were evaluated for diet and habitat. Bird species that do not consume seeds or grains as part of their diet and/or do not forage in areas where treated seeds may be used were excluded from the model. Diet and habitat information were gathered from US FWS documents, including the Biological Opinion for malathion (US Fish and Wildlife Service [US FWS], 2022) and the Cornell Lab of Ornithology, Birds of the World website (www.birdsoftheworld.org). The species that were removed because they do not consume or rarely consume seeds are listed in Supporting Information: Table SI-2.

The remaining 39 listed bird species may consume seeds or grains. These species were evaluated to determine those that could forage on agricultural fields and specifically on crops that may be planted with treated seeds. Species were screened out if they forage only in forests, in riparian wetlands, and in or over water. Those that forage in orchards or tree nuts, but not other crops, were also screened out because seed treatments are not used with these crops. Species that may forage on golf courses were included because turf seeds can be treated with pesticides. The species removed based on foraging habitat considerations are summarized in Supporting Information: Table SI-3.

The masked bobwhite (*Colinus virginianus ridgwayi*) was also removed from consideration because most individuals are in captivity in the Buenos Aires National Wildlife Refuge (BANWR), and all wild individuals are reintroduced from the captive population and live in a protected environment in the BANWR (US Fish and Wildlife Service [US FWS], 2019). Overall, 10 listed bird species have the potential for pesticide exposure from consuming treated seeds and were included in the ESASeedPARAM (Table 1). Species profiles and range maps of the 10 species included in the seed treatment model are provided in Supporting Information: Appendices A and B, respectively.

CO-OCCURRENCE OF SEED TREATMENT CROPS WITH LISTED BIRD SPECIES

Next, we determined the spatial co-occurrence of potential seed treatment crops with the ranges and critical habitats of the listed bird species included in the seed treatment model. Our co-occurrence analysis is a highly conservative, binary evaluation of the potential for an ESA-listed species to be exposed to a seed treatment pesticide for a particular crop.

The spatial data used to delineate crop footprints in the contiguous USA (CONUS) differ from those used for crop footprints outside the lower 48 states. The latter includes Alaska, Hawaii, and the US territories.

For the CONUS, the most recent available data (2014–2018) in the US Department of Agriculture (USDA) Cropland Data layer (CDL; US Department of Agriculture [USDA], 2019) were used to develop the crop footprints for potential seed treatment uses. The CDL crops were combined into the crop groups described by the North American Industry Classification System (NAICS) framework (Supporting Information: Table SI-4). Using the NAICS crop groupings lowers the uncertainty associated with misclassifying crops in the spatial analyses.

In some cases, the CDL may have misclassified areas or use sites. Therefore, additional spatial datasets were applied to address these spatial uncertainties. For example, the US Geological Survey (USGS) National Land Cover

TABLE 1 Listed bird species included in ESASeedPARAM

Common name (species)	Order	State or territory	Habitat
Attwater's greater prairie-chicken (*Tympanuchus cupido attwateri*)	Galliformes	TX	Native prairie; farmland
Hawaiian coot (*Fulica americana alai*)	Gruiformes	HI	Wetlands; golf courses
Hawaiian duck (*Anas wyvilliana*)	Anseriformes	HI	Ephemeral wetlands, stream systems; golf courses or rice
Hawaiian goose (*Branta [=Nesochen] sandvicensis*)	Anseriformes	HI	Grasslands, sparsely vegetated lava flows, cinder deserts, alpine grasslands and shrublands; golf courses and pastures
Gunnison sage-grouse (*Centrocercus minimus*)	Galliformes	CO, UT	Various sagebrush habitats; alfalfa, beans, wheat
Mariana common moorhen (*Gallinula chloropus guami*)	Gruiformes	Guam, Northern Mariana Islands	Freshwater lakes, marshes, swamps; rice
Mississippi sandhill crane (*Grus canadensis pulla*)	Gruiformes	MS, AL	Wet pine savanna; farmland
Puerto Rican plain pigeon (*Columba inornata wetmorei*)	Columbiformes	Puerto Rico	Edges of secondary forests; farmlands and plantations (grains)
Streaked horned lark (*Eremophila alpestris strigata*)	Passeriformes	OR, WA	Bare ground and low stature grasses and forbs; farmlands
Whooping crane (*Grus americana*)	Gruiformes	TX, OK, KS, NE, SD, ND, MT	Poorly drained potholes and wetlands; waste grains, corn

Database (NLCD) nonuse area layers were used as a mask on CDL data to screen out areas such as barren land, open water, forested areas, and developed areas. After reviewing many seed treatment labels, we eliminated NAICS crop groups that do not include crops for which seed treatments could be used currently (e.g., citrus groves, grape vineyards, tree nut farming).

The availability of spatial crop data for NL 48 areas is far more limited than for the contiguous USA. For Hawaii, the State of Hawaii Statewide Agricultural Land Use Baseline spatial dataset (http://hdoa.hawaii.gov/salub/) was supplemented with the USGS NLCD cultivated crops class (Class 82) and the pasture and hay class (Class 81). The NLCD was applied in Alaska as well, as no other agricultural crop data layer exists. In the territories, neither the CDL nor the NLCD are available. Therefore, other sources were used. The most recent dataset available from NOAA's Digital Coast Coastal Change Analysis Program (C-CAP) was used for each island and atoll (https://coast.noaa.gov/digitalcoast/data/ccapregional.html). This land cover dataset provides general classifications only, and the classification "Cultivated Crops" was used to represent potential seed treatment crops.

For each listed bird species included in the seed treatment model, the range was spatially delineated using the available maps from the US FWS (Supporting Information: Appendix B). An overlap analysis was then conducted at the county level of resolution for the listed bird species included in the seed treatment model. The NAICS crop use patterns that do not spatially co-occur with a listed bird species are not available for simulation in the ESASeedPARAM. The co-occurrence analysis was highly conservative because of the spatial resolution of the analysis (i.e., generally county level).

OVERVIEW OF THE SEED TREATMENT MODEL

As in previous probabilistic avian risk models developed for flowable pesticides (LiquidPARAM; Moore et al., 2014) and granular pesticides (GranPARAM; Moore et al., 2010a, 2010b), the ESASeedPARAM estimates exposure for each of 20 birds on each of 1000 fields for a total simulation of 20 000 birds per species (Figure 1). For each simulated bird, values are randomly selected for the input parameters required to estimate acute and chronic exposure. Once acute and chronic exposures to an individual have been estimated, a new individual is carried through the model. This process is repeated for a total of 20 individuals per field. The model then moves to the next field. The outer loop consisting of 1000 fields is designed to account for interfield variation in the amount of waste grain on the soil surface in tilled, reduced till (i.e., any minimal tillage system that leaves sufficient crop residue to cover the soil surface by at least 30%), and untilled fields.

The ESASeedPARAM estimates hourly intake of pesticide from ingestion of treated seeds for up to 50 days after planting. Roy et al. (2019) found that neonicotinoid concentrations on treated seeds remaining on the soil surface after planting decline rapidly (half-life = 2–4.7 days). The availability of treated seeds on or near the surface also declines due to wildlife consumption, germination, rotting, and other factors (Lennon et al., 2020). Thus, avian exposure to

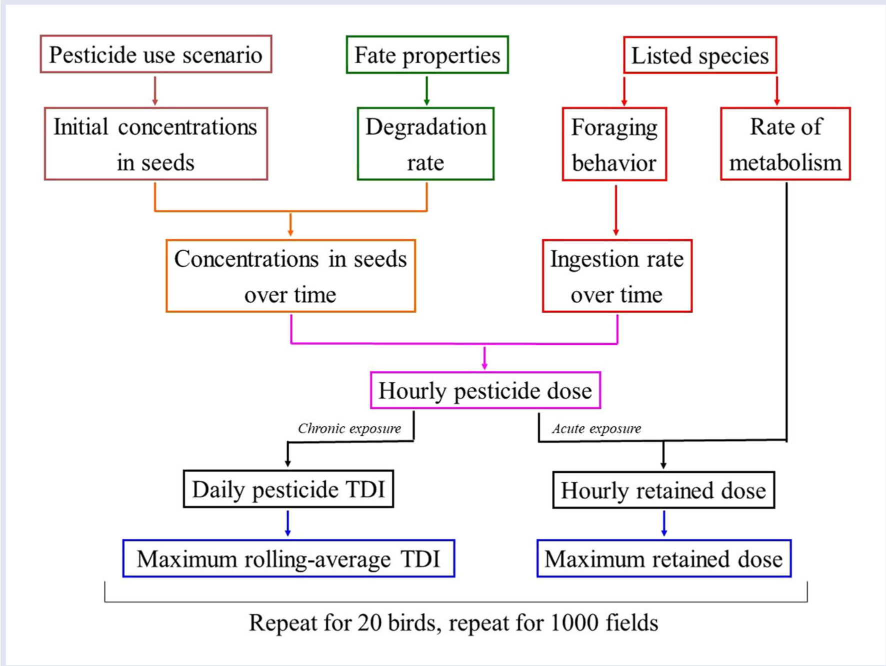

FIGURE 1 Exposure components of the ESASeedPARAM. TDI, total daily intake

neonicotinoids on treated seeds is likely to be negligible beyond 50 days after planting. The model user may specify the duration that treated seeds are available to birds after planting. Retained dose (mg ai/kg bw) is estimated for acute exposure to facilitate comparison with the acute oral ingestion toxicity endpoints (also, mg ai/kg bw). The retained dose at any given hour, *i*, is the hourly intake for that hour plus the retained dose remaining from the previous hour, $i-1$,

$$C_{\mathrm{bird,hour}_i} = HDI_i + C_{\mathrm{bird,hour}_{i-1}} \times RME,$$

where C_{bird} is the retained dose in mg ai/kg bw, *HDI* is hourly intake (mg ai/kg bw/h), and *RME* is the hourly rate of metabolism and elimination (h^{-1}). The acute exposure metric chosen by the model for comparison with the corresponding acute toxicity endpoint is the maximum $C_{\mathrm{bird,hour}_i}$ that occurred during the 50-day simulation. The approach to estimating retained dose has been used previously by Moore et al. (2010a, 2010b, 2014) and the USEPA (US Environmental Protection Agency [USEPA], 2015). Acute retained dose is often compared with the acute oral LD50 or other LDx because the latter is based on a gavage dose, which essentially is the retained dose shortly after administration. Ignoring metabolism and elimination would lead to greatly overestimated body burdens for seed treatment pesticides consumed over longer periods, particularly for pesticides that are rapidly metabolized and eliminated.

For chronic exposure, the model calculates the maximum rolling average total daily intake (expressed in mg ai/kg bw/day) that occurred during the 50-day simulation. The chronic exposure duration used to calculate rolling average total daily intake is user-entered and is typically based on the minimum duration of exposure that caused the most sensitive observed chronic effects for an apical endpoint in the corresponding toxicity study.

To estimate the fate of each bird from acute exposure to a seed treatment, a random value is selected from the appropriate dose–response relationship and compared with the maximum retained dose (Figure 2). If acute exposure (i.e., maximum retained dose) exceeds the randomly chosen effects value, mortality is assumed. If not, the bird is assumed to have survived. For chronic risk, the most sensitive No Observed Adverse Effects Level (NOAEL) and Lowest Observed Adverse Effects Level (LOAEL) for an apical endpoint (survival, growth, reproduction) from an acceptable study are selected. Where possible, the acute and chronic endpoints are matched at the taxonomic order level. Otherwise, the most sensitive apical acute and chronic endpoints are assumed irrespective of avian taxonomic order.

EXPOSURE COMPONENT OF THE SEED TREATMENT MODEL

Granivorous and omnivorous birds that could consume treated seeds from the soil surface also consume other available seeds including waste grain and weed seeds. Waste grain consists of crop seeds left on the soil surface after harvest and is an important food source for some birds in autumn and winter. Waste grain may also be an important food source into the following spring if left available because of no till or reduced till practices (Natural Resource Conservation Service [NRCS], 1999). The ESASeedPARAM has the option to consider the probabilities of birds consuming one or more treated seeds at each time step given measured densities of waste grain in tilled, reduced till, and untilled fields.

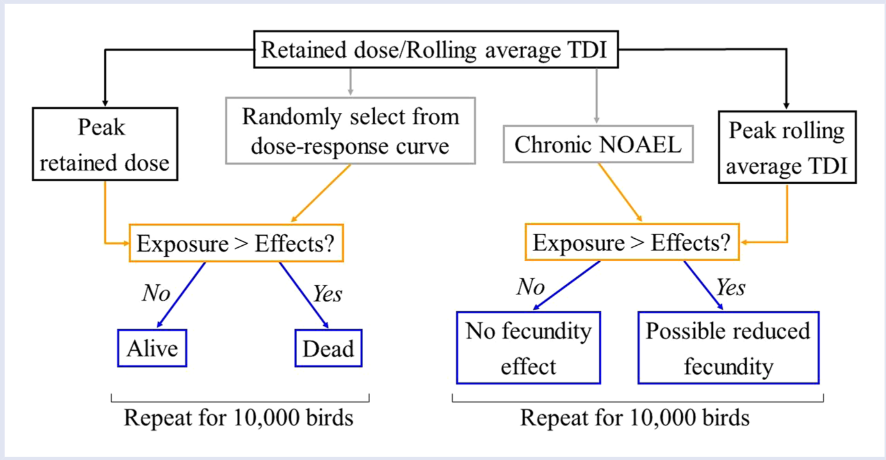

FIGURE 2 Effects and risk components of the ESASeedPARAM. TDI, total daily intake

Studies have demonstrated that granivorous and omnivorous birds are not attracted to recently tilled row crop fields (Galle et al., 2009; Warner et al., 1989). Tilling buries waste grains and weed seeds thus mostly eliminating the food resource that would attract granivorous birds. If 1% of treated seeds remain on the soil surface after planting (the USEPA's default assumption for precision drilling, in-furrow, t-banded, and shanked-in planting methods) in recently tilled fields, then there are likely insufficient seeds (e.g., approximately 400 and 2500 seeds/A for corn and soybean, respectively) to attract seed-eating birds. As a result, treated seeds in recently tilled fields generally pose a low risk to birds, particularly if best management practices are followed (e.g., precision drilling, cleaning up spills).

The default assumption in the ESASeedPARAM is that the entire portion of the diet of listed species consists of crop seeds, including treated seeds available from spring planting and waste grain available from the previous autumn harvest. The waste grain may be from the same crop being planted or from a different crop if crop rotation is being employed. If information is available to refine the default assumption (e.g., proportion of diet that comprises weed seeds and seeds from nonagricultural habitats), the user has the option to do so.

The ESASeedPARAM focuses only on dietary exposure arising from consumption of seeds on the soil surface. Dust-off during application may also occur and could lead to dermal and inhalation exposure (Schnier et al., 2003). Improvements to seed treatment and planting technology (e.g., American Seed Trade Association [ASTA] & CropLife America [CLA], 2017) are expected to have substantially reduced dust-off.

The inputs to the exposure component of the ESASeedPARAM are described in the following sections.

Food intake rate

Each hourly exposure is estimated by multiplying food intake rate by the proportion of seeds in the diet and hourly seed concentration. The following equation is used to estimate food intake rate:

$$FIR = \frac{FMR}{\sum_{i=1}^{n} AE_i \times GE_i},$$

where *FIR* is food intake rate (kg ww/kg bw/day), *FMR* is free metabolic rate (kcal/kg bw/day), AE_i is assimilation efficiency of the *i*th food item (unitless), and GE_i is gross energy of the *i*th food item (kcal/kg ww).

Several studies can be used to derive *FMR* equations for birds. We began by obtaining the data from reviews by Nagy et al. (1999) and Anderson and Jetz (2005). An open literature search performed on Google Scholar provided additional data on free-ranging birds. Preference was given to measured values for foraging juveniles and reproductively mature adults, which are the age classes most likely to forage on treated seeds. When multiple values were available for the same species, species means were calculated. The available data on FMR for birds are summarized in Supporting Information: Appendix C.

Allometric relationships were determined by power regression analysis comparing body weight (in g) and *FMR* (in kJ/day) using the data in Supporting Information: Appendix C. The general form of the model is:

$$FMR = a \times BW^b.$$

The slope (*a*) and power (*b*) parameters and unexplained sum of squares were based on a regression analysis of $\log_{10}$-transformed *FMR* and body weight inputs. Allometric equations were determined for all bird species combined as well as six taxonomic orders of birds that had sufficient data (i.e., ≥4 species). The relationship between *FMR* and body weight for all bird species is shown in Figure 3. In the ESASeedPARAM, *FMR* for each individual bird is estimated with a probabilistic approach by incorporating a distribution for body weight (*BW*) and by incorporating uncertainty resulting from lack of model fit (*LMF*) in the fitted allometric relationship (i.e., a normal distribution parameterized with a

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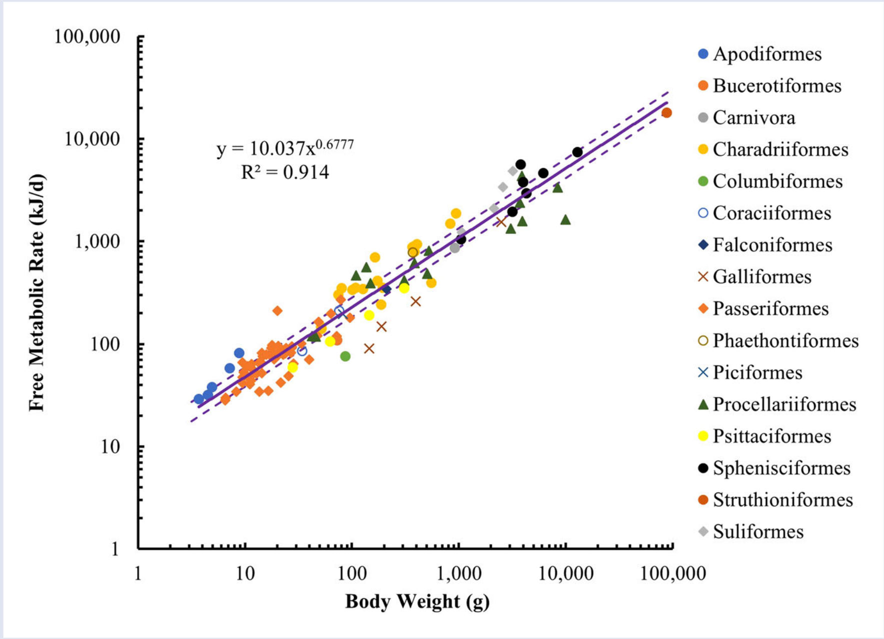

FIGURE 3 Free metabolic rate (*FMR*) fitted equation plus 95% confidence interval for all bird species

mean of 0 and a standard deviation calculated as the square root of the unexplained sum of squares from the fitted allometric regression model). The resulting equation for passerines is:

$$FMR\left(\frac{kJ}{d}\right) = 10^{1.04250} \times BW(g)^{0.63702} \times (LMF = 10^{N(0,0.12805)}),$$

where, N is a normal distribution with parameter mean and standard deviation in parentheses.

Sufficient data were available to generate six order-specific allometric equations (Supporting Information: Table SI-5). Of these, only the Galliformes and Passeriformes data correspond to listed bird species included in the ESASeedPARAM model. All other listed bird species rely on the allometric equation for all birds.

Body weight

For each of the 20 000 simulated birds in a model run, the ESASeedPARAM randomly selects whether the bird is male or female because many listed bird species, including those in the ESASeedPARAM, are dimorphic in body size (e.g., Gunnison sage-grouse). The model then randomly selects from a distribution of body weight specific to the sex of the listed species of interest. A normal distribution is assumed for body weight. The means and standard deviations used to parameterize the normal distributions for body weights of males and females of the listed species included in the ESASeedPARAM are in Supporting Information: Table SI-6.

Gross energy and percent moisture content

Gross energy (*GE*) and percent moisture content in dietary items along with *FMR* are required to estimate food intake rate for each simulated bird. Gross energy estimates were obtained primarily from Crocker et al. (2002) who determined mean energy and moisture contents for 15 dietary items. Crocker et al. (2002) reported dry weight gross energies. Therefore, wet weight values were determined by correcting for associated moisture contents. When multiple values were available for a receptor group, arithmetic means were determined. Supporting Information: Table SI-7 presents the mean gross energies and moisture contents determined for the dietary items included in the ESASeedPARAM.

Because GE is treated as a distribution for each dietary item, standard deviations are required in addition to the means. Although the *GE* values were primarily from Crocker et al. (2002), the study authors did not report standard deviations. Therefore, coefficients of variation (CVs) were calculated from the means and standard deviations reported in the Wildlife Exposure Factors Handbook (US Environmental Protection Agency [USEPA], 1993) for similar dietary items. The CVs were then applied to the means reported by Crocker et al. (2002) to estimate applicable standard deviations (Supporting Information: Table SI-7). In the ESASeedPARAM, a lognormal distribution was assumed for GE of each dietary item.

Assimilation efficiency

Assimilation efficiency (*AE*) is the proportion of energy an animal can acquire from a dietary item. This parameter depends on the physiology of the receptor consuming the dietary item and the characteristics of the dietary item itself. Assimilation efficiencies were obtained primarily from the USEPA (US Environmental Protection Agency [USEPA], 1993) and are summarized in Supporting Information: Table SI-8. Because assimilation efficiencies can only vary from 0 to 1, we used the reported means and standard deviations to inform the selection of parameter values for beta distributions (i.e., alpha, beta, minimum, maximum; Supporting Information: Table SI-8). Each randomly chosen value from a beta distribution for a dietary item of a bird was further scaled according to the equation:

$$AE_{\mathrm{scaled}} = AE_{\mathrm{min}} + (AE_{\mathrm{max}} - AE_{\mathrm{min}}) \times AE_{\mathrm{random}}. \quad (1)$$

Availability of treated seeds

Many labels for seed treatment pesticide formulations require that planted seeds be covered with soil and that seeds spilled during loading be covered or collected. To meet these requirements, precision drilling is often conducted. The use of precision-drilling equipment involves a metered machine releasing evenly spaced seeds in a furrow followed by furrow closing. A Dutch study revealed that precision drilling had an overall incorporation efficiency of 99.5%, whereas standard drilling in spring and autumn had efficiencies of 96.7% and 90.8%, respectively (de Snoo & Luttik, 2004). In avian risk assessments for seed treatment pesticides prepared by the USEPA, an incorporation efficiency of 99% has been previously assumed (e.g., US Environmental Protection Agency [USEPA], 2004a, 2005, 2010a). This value is slightly conservative for precision drilling compared with the results of de Snoo and Luttik (2004). In the ESASeedPARAM, the percentage of treated seeds that remain on the soil surface after planting is a user-defined option.

Waste grain on the soil surface

The number of birds foraging on a field depends on the amount of waste grain and vegetative cover during autumn and winter, among other factors (Basore et al., 1986; Galle et al., 2009; Warner et al., 1985, 1989). Waste grain are crop seeds left on the soil surface after harvest. Harvesting is not 100% efficient and waste grain may provide an important food source for wildlife in autumn and winter (Alisauskas et al., 1988; Baldassarre et al., 1983; Reinecke & Krapu, 1986; Ringelman, 1990; Warner et al., 1985). Waste grain may be available into the following spring with the quantity available being a function of harvest efficiency and tillage practice (Barney, 2008; NRCS, 1999; Warner et al., 1989).

The amount of waste grain differs considerably by crop and tillage system. Moldboard plowing in autumn eliminates 99% of waste corn and soybean, whereas reduced autumn tillage reduces waste grain by 65%–80% (Warner et al., 1985, 1989). Reduced tillage refers to partial- and non-inversion soil preparation methods that result in intermediate soil disturbance (e.g., disking, chisel plowing). Conservation tillage is designed to maintain adequate protection from erosion with a third or more of the soil surface covered by residue from the previous crop at spring planting (Warner et al., 1989). Baldassarre et al. (1983) estimated that tillage reduces waste grain availability in corn fields by 90%.

In a study in southern Ontario, Canada, Barney (2008) found that, in untilled fields, waste corn declined by approximately two-thirds after harvest in 2004 and 2005 to the following in spring in 2005 and 2006. Although sample size was limited, the decline in availability of waste grain from autumn to spring was much greater in tilled fields, that is, 97%, as was also observed by Warner et al. (1989).

Supporting Information: Table SI-10 summarizes the estimated amounts of waste grain after harvest and at planting the following season for different tillage practices. The estimates for the latter are based on the results of Warner et al. (1989) for corn and soybean, and thus there is uncertainty because seeds differ in size and degradability over time. The amounts of waste grain remaining after harvest are from Ringelman (1990) for barley, grain sorghum, Japanese millet, rice, and wheat. For barley, beans, flax, oats, oilseed rape and canola, peas, safflower, and sunflower, the estimates assume 95% harvest efficiency (i.e., 5% of the yield remains as waste grain), which is the average of the crops included in Ringelman (1990). In the ESASeedPARAM, the user may change the values listed in Supporting Information: Tables SI-9 and SI-10 if additional data become available or to investigate other scenarios.

Seeds of several crops are highly unlikely to be consumed by birds including the listed species in the ESASeedPARAM. Cotton seeds, for example, contain gossypol that is toxic to and thus avoided by birds (Henry et al., 2001; Ilyas et al., 2007; Janzen, 1971; Kakani et al., 2010; Smith & Pesti, 1998). Martin et al. (1951) compiled data from stomach contents analyses of wildlife in agroecosystems and found that "some major crops such as cotton, tobacco, sugar beets [though skylarks consume sugar beet cotyledons after germination; Green, 1980], and potatoes do not benefit wildlife much, if at all." Given that birds are highly unlikely to consume cotton and sugar beet seeds, and tobacco seedlings (which are grown in nurseries and thus not available to birds), we conclude negligible risk to birds consuming treated seeds, seed pieces, or seedlings for these crops. Therefore, there is no need to conduct simulations in the ESASeedPARAM for cotton, sugar beets, and tobacco. In addition, soybean seeds have digestive inhibitors that decrease appetite and cause weight loss (Dabbert & Martin, 1994; Diaz, 1990; Kendeigh & West, 1965; Warner et al., 1989). Thus, if soybean seeds found on the field are consumed, they are likely to account for only a minor portion of the diet (e.g., Alisauskas et al., 1988; Gates et al., 2001).

For each field in the ESASeedPARAM ($n = 1000$), the number of waste grains on the soil surface is randomly selected from a lognormal distribution with a mean and standard deviation as specified in Supporting Information: Table SI-10. This information is then used to determine the proportion of treated seeds on the soil surface for each field, that is, # treated seeds/(# treated seeds + # waste grains).

Number of aboveground treated seeds consumed

For each bird in a simulation, the average number of aboveground crop seeds (including treated seeds and waste grain) consumed is determined by dividing the seed ingestion rate (i.e., food ingestion rate × proportion seeds in the diet, kg ww/bird/h) by crop seed weight (kg ww) and multiplying the result by proportion of the diet from the treated field. The default for the latter is assumed to be 1 (i.e., entire diet from the treated field) to be conservative, but the user can change this value. The calculated number of aboveground crop seeds is an average value to meet the metabolic needs for the simulated individual. However, the number of actual seeds consumed will vary between time steps and is determined by randomly selecting from a Poisson distribution with a rate equal to the average number of aboveground crop seeds consumed by the individual bird corrected for daylength (a user-specified parameter, default = 14 h). Number of treated seeds consumed in each hourly time step is then determined by randomly selecting from a binomial distribution with parameters n (i.e., number of total crop seeds consumed in that hourly time step) and p (proportion of treated seeds on the soil surface).

Time to disappearance of treated seeds from the soil surface

Treated seeds left on the soil surface after planting disappear over time due to germination, consumption by wildlife, decay, and other factors. For example, Lennon et al. (2020) found that approximately 85% of treated wheat seeds on the soil surface disappeared by 14 days postplanting. However, few data are available to quantify the rate of disappearance of treated seeds from the soil surface for different crops. In addition, the rate of disappearance within a crop is likely to be highly variable temporally and spatially because of variation in attractiveness of fields to wildlife and environmental conditions (e.g., rain events, temperature). To be conservative, the ESASeedPARAM assumes no decline in availability of treated seeds over time. However, the user has the option to limit the duration of exposure to a fixed value. The default duration of exposure is 50 days, which is the simulation duration.

Initial seed concentration

To determine a time 0 concentration per seed in units of mg ai/kg seed, the seed loading rate in units of mg ai/seed and the average weight of seeds in units of g ww/seed are specified. Typical seed weights for different crops are summarized in Supporting Information: Table SI-10. This information can be adjusted by the user if a crop-specific seed weight is known.

Decline in concentration of active ingredient in seeds over time

Assuming first-order kinetics, the seed concentration at each hourly time step is determined using the equation:

$$C_{\mathrm{seed},t} = C_{\mathrm{seed},t-1} \times e^{\left(\frac{-0.693}{t_{1/2}} \times \frac{1}{24}\right)}, \tag{2}$$

where C_{seed} is concentration in the seed (mg ai/kg seed), $t_{1/2}$ is the half-life in days, t is the current hourly time step, and $t-1$ is the preceding time step. The model requires the user to enter a half-life for seed concentration.

Metabolism and elimination from birds over time

The amount of a pesticide retained by a bird from one hourly time step to the next is governed by the rate of metabolism and elimination:

$$HRD = HD_t + HRD_{t-1} \times f_{\mathrm{retained}}, \tag{3}$$

where HRD is hourly retained dose (mg ai/kg bw), t is the current time step, $t-1$ is the preceding time step, and f_{retained} is the fraction of the pesticide retained in the bird after accounting for metabolism and elimination. The retained fraction is determined using the equation:

$$f_{\mathrm{retained}} = e^{\frac{-0.693}{t_{1/2}} \times \frac{1}{24}}, \tag{4}$$

where $t_{1/2}$ is the half-life for metabolism and elimination in birds. The latter is a user-entered parameter in the model.

Diet

Information on diets of listed bird species was derived primarily from ECOS species profiles (www.ecos.fws.gov), US Fish and Wildlife Service (US FWS) listing documents, Supporting Information: Appendix C of the Biological Opinion for malathion (US Fish and Wildlife Service [US FWS], 2022), and the open literature. The available information on diets of listed bird species included in the ESASeedPARAM is summarized in Supporting Information: Table SI-11. The diets of the listed species as they are specified in the model are summarized in Table 2.

Proportion of diet from treated fields

Magnitude of exposure to treated seeds is linked to the proportion of time individual birds spend foraging on treated fields. Of the listed bird species included in the ESASeedPARAM, at least several would rarely forage in crop fields with treated seeds. For example, the Hawaiian duck (*Anas wyvilliana*) generally forages in water less than six inches deep (US Fish and Wildlife Service [US FWS], 2022). Although these ducks consume seeds, the seeds are from wetland plants and grass (US Fish and Wildlife Service [US FWS], 2022). Mississippi sandhill cranes (*Grus canadensis pulla*) are found only in Jackson County, MS, and reside primarily on or near the Mississippi Sandhill Crane

TABLE 2 Diets of listed bird species as specified in the ESASeedPARAM

	Proportion diet								
Common name (species)	Aboveground invertebrates	Grain/ seeds/nuts	Fruits	Short grass	Long grass	Broadleaf forage/flowers	Aquatic plants	Aquatic invertebrates	Fish/amphibians
Hawaiian (=koloa) duck (*Anas wyvilliana*)	0.14	0.22				0.05	0.09	0.45	0.05
Hawaiian goose (*Branta [=Nesochen] sandvicensis*)		0.01	0.18	0.52	0.21	0.08			
Gunnison sage-grouse (*Centrocercus minimus*)	0.34	0.06		0.01		0.59			
Puerto Rican plain pigeon (*Columba inornata wetmorei*)		0.2	0.8						
Streaked horned lark (*Eremophila alpestris strigata*)	0.656	0.344							
Hawaiian coot (*Fulica americana alai*)	0.15	0.15			0.14	0.14	0.14	0.14	0.14
Mariana common moorhen (*Gallinula chloropus guami*)	0.15	0.15			0.14	0.14	0.28	0.14	
Whooping crane (*Grus americana*)	0.02	0.07	0.35			0.02		0.52	0.02
Mississippi sandhill crane (*Grus canadensis pulla*)	0.03	0.3	0.3			0.3		0.05	0.02
Attwater's greater prairie-chicken (*Tympanuchus cupido attwateri*)	0.13	0.3	0.25		0.12	0.2			

National Wildlife Refuge (Gerber et al., 2014), which does not have cultivated crops with permitted seed treatment uses (US Fish and Wildlife Service [US FWS], 2007). Other listed bird species such as the Puerto Rican plain pigeon (*Columba inornata wetmorei*) supplement their diet with grass seeds and waste grain left over from farming activities (US Fish and Wildlife Service [US FWS], 2022), and the whooping crane (*Grus americana*) forages extensively in harvested grain fields, particularly during autumn migration (Johns et al., 1997).

Currently, no studies are available to quantify the proportion of the diet that comes from crop fields for the listed bird species included in the ESASeedPARAM. Thus, the default value for this input parameter is 1, which is highly conservative. The user has the option of changing this value in the model. Supporting Information: Appendix C in the final Biological Opinion for malathion (US Fish and Wildlife Service [US FWS], 2022) provides an overview of the diet and foraging habitats of each listed bird species in the ESASeedPARAM.

Effects and risk components of the ESASeedPARAM

The following procedure determines the fate of each bird for acute exposure. First, the standard normal *Z* score is calculated for the maximum retained dose (=body burden or whole-body tissue concentration). The *Z* score determines how extreme the exposure is relative to the appropriate LD50 assuming a log-probit dose–response relationship. The *Z* score ranges from near 0 for extremely low exposure relative to species sensitivity to near 1 for extremely high exposure relative to species sensitivity. The *Z* score is compared with a randomly selected value from a uniform distribution with a range of 0–1. If the *Z* score for exposure exceeds the randomly drawn value from the uniform distribution, the bird is assumed to die. Otherwise, it is assumed to survive (Figure 2).

The log-probit dose–response relationship selected for each species depends on the availability of acute toxicity data. If acute toxicity data from one or more acceptable studies are available for the taxonomic order to which the species belongs, then the lowest LD50 for the most sensitive test species from that taxonomic order is selected along with the average probit slope. The rationale for this approach derives from studies that have demonstrated strong relationships between taxonomic relatedness and sensitivity to pesticides (e.g., Guénard et al., 2014; Hylton et al., 2018; Moore et al., 2020; Spurgeon et al., 2020). Failing availability of toxicity data from the same taxonomic order, if there are sufficient data (i.e., six or more tested species in studies of acceptable quality) to derive an acute species sensitivity distribution (SSD), then the LD50 for the hypothetical 5th centile (i.e., sensitive) species is selected along with the average probit slope across all tested taxonomic orders. If no acute toxicity data are available from the same taxonomic order as the listed species of interest and there are insufficient data to derive an SSD, then the lowest overall LD50 is selected along with the average probit slope across taxonomic orders. The lowest NOAEL and LOAEL for an apical endpoint (survival, growth, reproduction) from an acceptable study are selected to estimate chronic risk. Where possible, the chronic endpoints are matched at the taxonomic order level; otherwise the lowest values are used.

Acute risk curves are derived for each combination of seed treatment crop and listed bird species by determining the percentages of fields that have more than 5% mortality (≥1/20 dead birds per field), more than 10% mortality (≥2/20 dead birds per field), approximately 15% mortality (≥3/20 dead birds per field), etc.). The result is a plot of exceedance probability versus magnitude of effect. Similar approaches have been used in ecological risk assessments performed for the USEPA at the Calcasieu Estuary in Louisiana, the Housatonic River in Massachusetts (US Environmental Protection Agency [USEPA], 2002, 2004b), and by others assessing the ecological risk of pesticides (Giddings et al., 2005; Moore et al., 2010a, 2010b, 2010c, 2014; Solomon et al., 2001). The percent of birds surviving is also calculated for each seed treatment crop and listed species. To determine chronic risk, the model calculates the percentages of birds with maximum rolling average total daily intake exceeding the corresponding NOAEL and LOAEL.

CASE STUDY: LISTED BIRD SPECIES EXPOSED TO IMIDACLOPRID-TREATED SEED IN SOYBEAN AND WHEAT

The imidacloprid formulations evaluated in this case study include AERIS, CONCUR, Gaucho 480, Gaucho 600, Raxil PRO SHIELD, and Sepresto 75 WS. All products require collection or covering of spilled treated seeds. The products are summarized in Table 3. We briefly describe the inputs and outputs for the case study below.

Application rates

For the case study, we assumed the highest calculated seed concentrations for soybean (i.e., 0.0988 mg ai/seed for GAUCHO 600) and wheat (i.e., 0.0150 mg ai/seed for GAUCHO 600). Seed weights of 0.162 g/seed for soybean (Integrated Pest Management [IPM], 2008) and 0.0328 g/seed for wheat (Bean et al., 2019) were assumed for this assessment. These seed weights are well within the ranges cited by the USEPA (US Environmental Protection Agency [USEPA], 2010b) for use as input values to calculate terrestrial residues from treated seed. Application rates for the two crops of interest are shown in Table 4.

Availability of treated seed and waste grain on the soil surface

Seed planting density is required to determine the number of treated seeds in a planted field. Roy et al. (2019) evaluated density of corn, soybean, and wheat seeds planted in agricultural fields in Minnesota, serving as a representative case study for the USA. Soybean seeding rates in Minnesota ranged from 140 000 to 170 000 seeds/A (345 948–420 079 seeds/ha), whereas

TABLE 3 Formulations containing imidacloprid and registered for use in the USA as seed treatments

Product	Imidacloprid (%)	Other active ingredients (%)	Crop
AERIS	24	Thiodicarb (24)	Cotton
CONCUR	25	Metalaxyl (1.0)	Corn, sorghum
Gaucho 480	40.7	-	Oil seed crops, corn (field, sweet, pop), wheat, barley, oats, rye, triticale, sorghum, millet, cotton (delinted) sugar beets, soybean, legume, carrot
Gaucho 600	48.7	-	Wheat, barley, oats, rye, triticale, sorghum, millet, cotton (delinted), oil seed crops, corn (field, sweet, pop), sugar beets, soybean, legume, carrot
Raxil PRO SHIELD	8.59	Prothioconazole (1.47), metalaxyl (0.57), tebuconazole (0.29)	Wheat, barley, triticale
Sepresto 75 WS	18.75	Clothianidin (56.25)	Carrot, onion (bulb and bunching), leek

summer wheat seeding rates ranged from 1 300 000 to 1 400 000 seeds/A (3 212 370 to 3 459 475 seeds/ha). The seeding densities assumed for the case study were 155 000 seeds/A (383 013 seeds/ha) for soybean and 1 350 000 seeds/A (3 335 923 sees/ha) for wheat, which were the median densities for each crop reported in Roy et al. (2019). We assumed the USEPA (US Environmental Protection Agency [USEPA]; 2013) default value of 0.01 (=1%) for precision drilling to determine the proportion of seeds remaining on the soil surface after planting.

In this case study, we estimated exposure and risk for three tillage practices in soybean and wheat: tilled, reduced till, and untilled. The amount of waste grain at planting assumed for each crop and tillage practice is in Supporting Information: Table SI-10.

Pesticide availability over time

A field study conducted in Minnesota quantified imidacloprid degradation rate in seeds left on the soil surface (Roy et al., 2019). In the study, treated seeds were broadcast on the soil surface of a tilled field and collected several times for subsequent chemical analysis. The half-life of imidacloprid on soybean seeds ranged up to 4.7 days. No comparable data are available for wheat. In this case study, a seed concentration dissipation half-life of 4.7 days was assumed for both soybean and wheat. To be conservative, we assumed no decline in availability of treated seeds over the full model duration of 50 days.

Listed species

Only those listed bird species that could co-occur with soybean or wheat fields were considered in the case study for imidacloprid seed treatment. Based on the co-occurrence analysis described earlier, all species included in the model (Table 1), except for the streaked horned lark, could co-occur with soybean. Only the streaked horned lark could co-occur with wheat. The input values assumed for each species are in Table 2 for diet, Supporting Information: Table SI-5 for free metabolic rate, and Supporting Information: Table SI-6 for body weight.

Avian metabolism and elimination half-life

Bean et al. (2019) dosed adult male Japanese quail (*Coturnix japonica*) with wheat seeds treated with SATIVA IMF Max that contained 9.04 μg imidacloprid per seed (0.276 mg ai/g seed). Doses of imidacloprid were 0.9 or 2.7 mg ai/kg bw in the form of gelatin capsules containing treated seeds. Complete excretion and elimination of imidacloprid occurred within 24 h of dosing. The metabolism and elimination half-life was estimated to be 3 h (=0.235 days), and this was the value assumed in

TABLE 4 Application rates for imidacloprid seed treatments

Crop	Formulation	Concentration (fl oz/100 lb seed)	Seed weight (g)	Concentration (mg ai/seed)
Soybean	GAUCHO 480	4	0.162	0.0826
	GAUCHO 600	3.2	0.162	0.0988
Wheat	GAUCHO 480	3	0.0328	0.0125
	GAUCHO 600	2.4	0.0328	0.0150
	Raxil PRO SHIELD	-	-	0.0105

the case study. Neither dose nor duration of exposure affected the estimated half-life.

Toxicity endpoints

Acute toxicity data were available for eight species across four orders of birds: Galliformes, Anseriformes, Passeriformes, and Columbiformes (Table 5). Toxicity studies for the Japanese quail (Grau, 1988; Schmuck, 1997), northern bobwhite (Toll, 1990), mallard (Hancock, 1996), house sparrow (Stafford, 1991), grayish baywing (Poliserpi et al., 2021), and eared dove (Addy-Orduna et al., 2019) followed standard toxicity testing guidelines and included detailed descriptions of study methodology. These studies were considered acceptable for use in this case study, consistent with the USEPA's classification of study quality (US Environmental Protection Agency [USEPA], 2017). Several studies did not follow standard testing guidelines, did not include detailed descriptions of methods, and thus were considered unacceptable for use in the case study. The acute toxicity endpoint for the most sensitive species from an acceptable study was used for each order (bolded values in Table 5). The Japanese quail endpoint was assumed for any listed species in a taxonomic order not represented by available acute toxicity data.

Two chronic avian toxicity studies are available for imidacloprid. Toll (1991a) exposed male and female mallard ducks (*Anas platyrhynchos*) to imidacloprid in the diet for 21 weeks. There were no treatment-related effects to survival or behavior. However, there were significant reductions in mean number of eggs laid, mean number of eggs hatched, and number surviving to 14 days in the highest treatment group. The NOAEL was 12.9 mg ai/kg bw/day (125 mg ai/kg diet), and the LOAEL was 24.1 mg ai/kg bw/day (234 mg ai/kg diet) for females. No significant effects to males were observed in any treatment. Toll (1991b) exposed male and female northern bobwhite (*Colinus virginianus*) to imidacloprid in the diet for 20 weeks. There were no effects on reproduction. The only effect observed was a significant reduction in male body weight at test end, resulting in a NOAEL of 8.9 mg ai/kg bw/day (126 mg ai/kg diet) and a LOAEL of 17.3 mg ai/kg bw/day (243 mg ai/kg diet). The toxicity endpoints used in the case study were matched at the taxonomic order level if available. For species not represented by Anseriformes (mallard toxicity study) or Galliformes (northern bobwhite toxicity study), the most sensitive Galliformes NOAEL and LOAEL were assumed. The chronic averaging periods selected were 28 days for Anseriformes based on significant effects during the reproductive period and 30 days for the northern bobwhite (Galliformes and all other orders)

TABLE 5 Acute toxicity data for birds exposed to imidacloprid

Order	Species	LD50 (mg ai/kg bw)	Probit slope	Study quality	Reference
Galliformes	Gray partridge (*Perdix perdix*)	~15		Supplemental—lacks some details	Grolleau (1990)
	Japanese quail (*Coturnix japonica*)	**24.2**	**3.77**[a]	Acceptable	Schmuck (1997)
		31	2.40	Acceptable	Grau (1988)
	Northern bobwhite (*Colinus virginianus*)	152	2.66	Acceptable	Toll (1990)
Anseriformes	Mallard (*Anas platyrhynchos*)	95.6		Supplemental—only 2 or 3 ducks per dose	Watanabe (1989)
		283	**6.63**	Acceptable	Hancock (1996)
Passeriformes	Canary (*Serinus canaria*)	>25 < 50	-	Unacceptable—study report lacks key details	Grau (1986)
	House sparrow (*Passer domesticus*)	**41.0**	**2.48**[a]	Acceptable	Stafford (1991)
	Grayish baywing (*Agelaioides badius*)	57.1	4.12	Acceptable	Poliserpi et al. (2021)
Columbiformes	Domestic pigeon (*Columba livia*)	>25 < 50		Unacceptable—study report lacks key details, only 4 birds per dose	Grau (1987)
	Eared dove (*Zenaida auriculata*)	**59.0**	**6.80**	Acceptable	Addy-Orduna et al. (2019)

Note: Bolded values indicate toxicity endpoints used in the imidacloprid case study.
[a]LD50 and slope calculated using probit analysis in R *drc* package (Ritz et al., 2015).

based on the maximum duration allowed by the ESASeedPARAM because effects were only observed at test termination.

Risk estimates

The acute and chronic risk results are summarized in Tables 6 and 7, respectively. As expected, risk was highest for tilled fields and lowest for no till fields. Reduced and no till planting scenarios had very low mortality, and fewer than 0.1% of individuals had exposures that exceeded the chronic NOAEL for all species.

For tilled soybean fields, the Hawaiian coot, Mississippi sandhill crane, and Attwater's greater prairie-chicken had low predicted mortality, and the Mariana common moorhen had somewhat elevated predicted mortality. All other species had very low predicted mortality for tilled soybean fields. For tilled wheat fields, the streaked horned lark also had an elevated predicted mortality (Figure 4). Chronic risk

TABLE 6 Acute exposure and risk results for imidacloprid-treated seeds case study

			Maximum retained dose (mg ai/kg bw)						
Crop	Species	Tillage practice	Mean	25th percentile	50th percentile	75th percentile	Minimum	Maximum	% Birds surviving
Soybean	Hawaiian duck (*Anas wyvilliana*)	No till	1.67	0.941	1.40	2.10	0.132	13.2	100
		Reduced till	2.46	1.39	2.06	3.09	0.195	17.2	100
		Tilled	12.9	8.75	11.8	15.8	1.58	62.8	100
	Hawaiian goose (*Branta [=Nesochen] sandvicensis*)	No till	0.128	0.076	0.11	0.16	0.00853	1.06	100
		Reduced till	0.171	0.101	0.15	0.22	0.0177	1.05	100
		Tilled	0.751	0.492	0.680	0.930	0.0705	3.96	100
	Gunnison sage-grouse (*Centrocercus minimus*)	No till	0.318	0.211	0.29	0.39	0.0502	1.35	100
		Reduced till	0.441	0.294	0.40	0.55	0.0486	1.86	100
		Tilled	2.13	1.82	2.10	2.41	0.807	4.61	100
	Puerto Rican plain pigeon (*Columba inornata wetmorei*)	No till	1.83	1.05	1.54	2.28	0.123	14.0	100
		Reduced till	2.61	1.50	2.22	3.28	0.220	20.3	100
		Tilled	13.2	8.72	12.0	16.3	1.21	59.0	99.8
	Hawaiian coot (*Fulica americana alai*)	No till	1.34	0.781	1.14	1.66	0.0943	10.1	100
		Reduced till	1.97	1.12	1.65	2.46	0.161	14.3	100
		Tilled	10.4	7.07	9.49	12.8	1.54	55.4	93.0
	Mariana common moorhen (*Gallinula chloropus guami*)	No till	1.75	1.03	1.49	2.18	0.185	15.7	100
		Reduced till	2.54	1.46	2.15	3.18	0.228	16.4	100
		Tilled	12.6	8.46	11.4	15.4	1.62	59.6	87.8
	Whooping crane (*Grus americana*)	No till	0.384	0.211	0.320	0.480	0.0241	3.17	100
		Reduced till	0.586	0.320	0.490	0.750	0.0390	5.10	100
		Tilled	3.44	2.33	3.13	4.18	0.528	13.3	99.9
	Mississippi sandhill crane (*Grus canadensis pulla*)	No till	0.810	0.424	0.660	1.03	0.0504	7.30	100
		Reduced till	1.23	0.644	1.01	1.56	0.103	9.69	100
		Tilled	7.23	4.92	6.61	8.94	0.691	23.7	97.9
	Attwater's greater prairie-chicken (*Tympanuchus cupido attwateri*)	No till	0.792	0.504	0.710	0.980	0.108	4.13	100
		Reduced till	1.16	0.745	1.04	1.45	0.154	5.01	100
		Tilled	5.94	4.94	5.82	6.79	2.05	15.2	98.6
Wheat	Streaked horned lark (*Eremophila alpestris strigata*)	No till	1.48	1.03	1.36	1.80	0.192	7.73	100
		Reduced till	2.91	2.09	2.71	3.51	0.553	14.2	99.7
		Tilled	16.5	12.1	15.6	19.9	3.43	57.7	83.7

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TABLE 7 Chronic exposure and risk results for imidacloprid-treated seeds case study

Crop	Species	Tillage practice	Maximum rolling average total daily intake (mg ai/kg bw/day) Mean	25th percentile	50th percentile	75th percentile	Minimum	Maximum	% Exceeding NOAEL	% Exceeding LOAEL
Soybean	Hawaiian duck (*Anas wyvilliana*)	No till	1.01	0.493	0.804	1.30	0.0262	9.93	0	0
		Reduced till	1.59	0.808	1.29	2.03	0.0640	12.3	0	0
		Tilled	9.75	6.49	8.85	12.0	0.957	48.7	20.2	1.30
	Hawaiian goose (*Branta [=Nesochen] sandvicensis*)	No till	0.0518	0.0228	0.0394	0.07	0.000512	0.794	0	0
		Reduced till	0.0787	0.0363	0.0617	0.10	0.00194	0.686	0	0
		Tilled	0.489	0.298	0.434	0.620	0.0237	2.81	0	0
	Gunnison sage-grouse (*Centrocercus minimus*)	No till	0.148	0.0864	0.128	0.190	0.0126	0.742	0	0
		Reduced till	0.229	0.138	0.203	0.290	0.0130	1.03	0	0
		Tilled	1.42	1.22	1.40	1.60	0.413	3.01	0	0
	Puerto Rican plain pigeon (*Columba inornata wetmorei*)	No till	0.926	0.436	0.724	1.17	0.0182	9.01	0	0
		Reduced till	1.45	0.709	1.17	1.88	0.0315	15.5	0.0850	0
		Tilled	9.06	5.77	8.14	11.2	0.662	43.5	42.6	5.79
	Hawaiian coot (*Fulica americana alai*)	No till	0.725	0.367	0.586	0.920	0.0217	5.71	0	0
		Reduced till	1.16	0.579	0.925	1.47	0.0465	9.66	0.0150	0
		Tilled	7.29	4.83	6.59	8.99	0.885	36.7	25.7	1.68
	Mariana common moorhen (*Gallinula chloropus guami*)	No till	0.865	0.42	0.691	1.11	0.0327	10.9	0.00500	0
		Reduced till	1.39	0.688	1.12	1.78	0.0511	11.1	0.0400	0
		Tilled	8.52	5.57	7.73	10.50	0.839	42.4	37.8	3.89
	Whooping crane (*Grus americana*)	No till	0.256	0.131	0.206	0.320	0.0123	2.14	0	0
		Reduced till	0.403	0.208	0.333	0.520	0.0154	3.81	0	0
		Tilled	2.51	1.70	2.29	3.06	0.349	9.70	0.0350	0
	Mississippi sandhill crane (*Grus canadensis pulla*)	No till	0.556	0.274	0.442	0.710	0.0233	5.05	0	0
		Reduced till	0.861	0.433	0.702	1.10	0.0525	6.91	0	0
		Tilled	5.31	3.60	4.84	6.58	0.513	17.4	8.73	0.005

(*Continued*)

TABLE 7 *(Continued)*

Crop	Species	Tillage practice	Maximum rolling average total daily intake (mg ai/kg bw/day) Mean	25th percentile	50th percentile	75th percentile	Minimum	Maximum	% Exceeding NOAEL	% Exceeding LOAEL
	Attwater's greater prairie-chicken (*Tympanuchus cupido attwateri*)	No till	0.427	0.245	0.370	0.550	0.0273	2.70	0	0
		Reduced till	0.679	0.403	0.601	0.870	0.0555	3.18	0	0
		Tilled	4.14	3.46	4.06	4.72	1.51	9.95	0.015	0
Wheat	Streaked horned lark (*Eremophila alpestris strigata*)	No till	0.545	0.327	0.474	0.690	0.0337	3.52	0	0
		Reduced till	1.42	0.958	1.30	1.74	0.164	8.58	0	0
		Tilled	11.0	7.86	10.3	13.3	1.92	39.0	64.6	8.27

was greatest for the Hawaiian duck, Puerto Rican plain pigeon, Hawaiian coot, Mariana common moorhen, and Mississippi sandhill crane for treated soybean seed, and streaked horned lark for treated wheat seed. For these species, 8.73%–64.6% had predicted chronic exposure exceeding the NOAEL and fewer than 9% exceeding the LOAEL.

Other considerations for listed species potentially at risk to imidacloprid-treated seeds

The streaked horned lark primarily consumes grass and forb seeds, and some insects (Beason, 1995). In agricultural areas, the species is attracted primarily to areas in or adjacent to grass seed fields, pastures or fallow fields, recently planted conifer farms, and wetland mudflats or washed-out agricultural fields (Federal Register [FR], 2021). Of particular importance is grass seed fields, the primary food source for streaked horned larks in the Willamette Valley where it is found. The main threat to the species is habitat loss. Grass seed production makes up approximately half of the agriculture in the Willamette Valley, but recent reductions in grass seed production have led some growers to switch commodities. Wheat is one such commodity but does "not have the low-statured vegetation and bare ground preferred by the streaked horned lark (Federal Register [FR], 2021)." Therefore, the assumed time spent foraging on treated fields (i.e., 100%) is likely highly conservative.

The Marianna common moorhen, Hawaiian coot, and Hawaiian duck had higher risk estimates for tilled soybean fields than other species. These species have a high affinity for water and are primarily found in and around wetlands (Byrd et al., 1985; US Fish and Wildlife Service [US FWS], 1991, 2011). Interaction with agriculture is restricted to rice paddies, taro ponds, and golf courses. Therefore, the likelihood of exclusively foraging on soybean fields for 50 days immediately following planting is very low for these species.

The physiological size limitations of some bird species limit their ability to ingest large seeds. For example, many passerines less than 100 g in size could not easily consume whole soybeans (Bean et al., 2019). Because of limited information on preferred seed sizes for listed bird species and to be conservative, seed size was not considered in the development of the ESASeedPARAM. Size of mouthparts and stomachs of birds would directly influence the type and quantity of seeds listed birds could consume. Bean et al. (2019) performed a controlled laboratory study where Japanese quail were gavage-dosed with wheat seeds coated with imidacloprid for 1–10 days. A maximum dose of 2.7 mg ai/kg bw could be administered based on the maximum number of coated seeds that could be ingested at one time by birds. This dose is well below the median lethal dose for tested bird species (Table 5).

Conservation tillage that retains at least 30% of field residue cover at planting has been adopted by farmers to reduce soil disturbance and conserve soil health and water (Classen et al., 2018). Conservation tillage also reduces fuel, labor, and tillage machinery costs. Untilled and reduced till

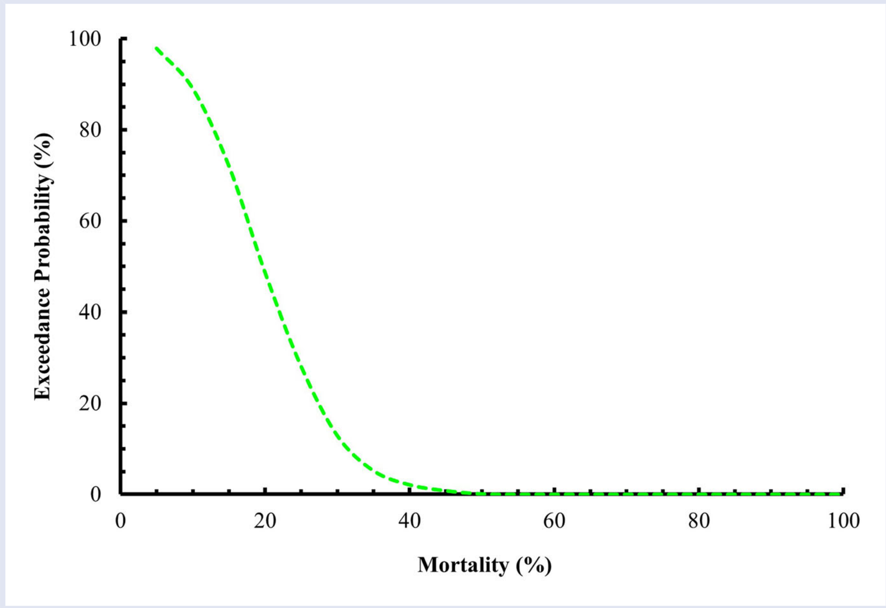

FIGURE 4 Exceedance probability versus estimated mortality of streaked horned larks on tilled wheat fields with imidacloprid-treated seeds. The simulation included 1000 fields with each tilled wheat field having 20 birds

fields have far greater quantities of waste grain and weed seeds, which would have negligible levels of neonicotinoids, than treated seeds on the soil surface (Warner et al., 1985, 1989). As a result, the probability of birds consuming one or more treated seeds is greatly reduced. A US Department of Agriculture report concluded that no till practices are expected to steadily increase in use in the future (Horowitz et al., 2010). Classen et al. (2018) demonstrated an increase in conservation tillage of wheat in the USA from 37% in 2004 to 67% in 2017. Conservation tillage in soybean fields in the USA increased from 62% in 2002 to 70% in 2012 (Classen et al., 2018). A strong preference for reduced till practices in the USA, particularly in recent decades, greatly reduces the risk of seed treatment pesticides to listed granivorous and omnivorous bird species.

Our seed treatment model indicated risk for several listed bird species to imidacloprid used as a seed treatment on fully tilled fields. However, given the habitat and foraging preferences of these species and several highly conservative assumptions due to data limitations, risk was likely overestimated. The case study demonstrated that no till and reduced till practices greatly reduce the risk to listed seed-eating bird species. Continued use of these practices would reduce risk to listed and other bird species.

Sources of uncertainty in the ESASeedPARAM

Where possible, sources of uncertainty were quantified and incorporated in the model (e.g., *FMR*, abundance of waste grain on the soil surface). Thus, these sources of uncertainty have been explicitly accounted for in the ESASeedPARAM. Other sources of uncertainty, however, could not be fully accounted for in the model, generally because data were too scarce to reliably parameterize distributions (e.g., proportion time foraging on fields with treated seeds, time to disappearance of seeds from the soil surface). The potential influence of these variables on estimated exposure is described below.

- Information is lacking to fully characterize between-field, between-individual, and between time steps variability in proportion of time listed bird species forage on treated fields. Therefore, the default assumption is that birds obtain 100% of the seed component of their diet from treated fields. This is a highly conservative assumption, particularly for tilled fields, which are generally unattractive to foraging granivorous birds (McGee et al., 2018). The default value may be changed by the user if information is available to justify a more realistic input.
- Information is lacking on the number of waste grains remaining on the soil surface for many crops, particularly at the time when treated seeds are planted. Our recommended values for this variable by crop, tillage practice, and season (Supporting Information: Table SI-10) are mostly extrapolated from field observations for corn and soybean (e.g., Barney, 2008; Warner et al., 1985, 1989). Thus, there is uncertainty regarding the number of waste grains available to birds for most crops. The user has the option to enter zero for this variable to be highly conservative or another value if better information becomes available.
- The ESASeedPARAM assumes that birds consume bean, corn, pea, and soybean seeds although these crop seeds are fairly large. Smaller listed bird species such as the streaked lark (*Eremophila alpestris strigata*), however, may not be able to consume such large seeds.
- The available toxicity data will likely be limited for acute and chronic exposure durations of listed bird species in

some taxonomic orders. In the absence of order-specific toxicity data, the ESASeedPARAM assumes the most sensitive available LD50, NOAEL, and LOAEL.

- For acute effects, the model relies on the results of acute oral gavage studies. Oral gavage exposure does not accurately reflect exposure in the field. Oral gavage studies do not account for the influence of natural dietary matrices, feeding patterns, metabolism, and elimination throughout the day.

CONCLUSIONS

In the USA, up to 10 listed bird species could be exposed to seed treatment pesticides used in crops such as corn, soybean, cereals, vegetables, hay, and turf. To our knowledge, the USEPA and other government agencies do not currently have a refined probabilistic seed treatment assessment model for listed or other bird species. Therefore, we developed a refined model, the ESASeedPARAM, to assess the risks of seed treatments to listed bird species in the USA. The model incorporates species-specific diets, body weights, and food ingestion rates and incorporates information on the availability of waste grain, dissipation of seed residues after planting, and metabolism and elimination by birds during and after exposure. Although the ESASeedPARAM is a refined model, the model is deliberately conservative where there are significant data gaps (e.g., length of time treated seeds are available to birds after planting, proportion of time listed bird species forage on treated fields, and proportion of seeds in the diet that are crop seeds). The model is flexible and can be made more realistic as data gaps are addressed. The ESASeedPARAM could be expanded to include nonlisted bird species in the USA and elsewhere although extensive research would be required to determine which species potentially co-occur with seed treatment crops and, for those that do, their diets, body weights, and foraging behaviors.

To illustrate the ESASeedPARAM, we conducted a case study for imidacloprid-treated seeds used in soybean and wheat. The case study revealed that imidacloprid-treated seeds planted in reduced and no till fields pose little risk to listed bird species. Greater risks were predicted for several listed bird species foraging in tilled fields because of the absence of weed seeds and waste grains whose presence would make consumption of treated seeds much less likely to occur. The case study was highly conservative as we assumed that all dietary ingestion of seeds was from treated fields. This and several other assumptions were not realistic, particularly for listed bird species that have specialized habitat and dietary requirements. Although risk cannot be ruled out for several listed species foraging in tilled fields in the case study, other lines of evidence and the conservatism inherent in the ESASeedPARAM suggest that risks are likely low and possibly negligible. Conclusions from the imidacloprid case study can be taken as a likely worst case pending further refinement.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

DISCLAIMER

The peer review for this article was managed by the Editorial Board without the involvement of D. Moore.

AUTHOR CONTRIBUTIONS

Dwayne R. J. Moore: Conceptualization; Data curation; Formal analysis; Funding acquisition; Methodology; Software; Supervision; Writing—original draft; Writing—review & editing. **Colleen D. Priest**: Data curation; Formal analysis; Writing—original draft.

DATA AVAILABILITY STATEMENT

All raw data are provided in the Supporting Information. Questions regarding the raw data may be directed to author Dwayne Moore (dmoore@intrinsik.com). To obtain copies of unpublished reports cited in the paper, please send requests to cropscience-transparency@bayer.com.

SUPPORTING INFORMATION

Table SI-1: Listed bird species that are extinct, extirpated, found only in remote areas where seed treatments would not be used or restricted to captivity (US FWS, 2022).

Table SI-2: Listed bird species that do not or rarely consume seeds.

Table SI-3: Listed bird species that do not forage in areas where treated seeds would be planted.

Table SI-4: North American Industry Classification System (NAICS).

Table SI-5: Allometric equations for listed bird species. *FMR* (free metabolic rate) is in kJ/day and *BW* (body weight) is in g.

Table SI-6: Body weight parameters for listed bird species included in the ESASeedPARAM.

Table SI-7: Gross energy parameter values (all data from Crocker et al., 2002).

Table SI-8: Assimilation efficiencies of dietary items (all data from USEPA, 1993).

Table SI-9: Waste grain on the soil surface in the spring.

Table SI-10: Estimated waste grain on the soil surface after harvest and at planting.

Table SI-11: Dietary information for listed bird species included in the ESASeedPARAM.

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