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Comparison of two models for estimating mortality from baitings with Compound DRC-1339 Concentrate avicide

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ABSTRACT

In the U.S., DRC-1339 baitings for blackbirds (Icteridae) are generally done under the pesticide label, Compound DRC-1339 Concentrate – Staging Areas. DRC-1339 is a slow-acting avicide and gives the birds enough time to leave the baiting sites. Carcass searches and other forms of onsite counts are ineffective. Instead, linear models (LM) are used. The LM are based on esophageal analyses of several blackbird species collected while feeding at staging area bait sites. Biases and large variances can occur with this type of sampling. As an alternative to the LM, we developed a semi-mechanistic model (SM) that combined mechanistic modeling of environmental and biophysical processes with statistical modeling of DRC-1339 toxicities, avian physical and physiological traits, and foraging behavior. We used simulated baiting scenarios in Missouri and Louisiana to quantify and compare mortality between the LM and SM. The SM accounted for meteorological and regional effects on feeding rates, and we ran the SM scenarios for both mild and inclement weather conditions during January, a month when DRC-1339 baitings frequently occur. Mortality was calculated for males and females of three blackbird species. We used brown rice as the delivery substrate in a mix consisting of 11.34 kg untreated and 0.45 kg 2% DRC-1339 treated rice (1:25 dilution ratio). Compared to the LM, estimates by the SM ranged from 5% higher for male common grackles [*Quiscalus quiscula* L] to 59% lower for male brown-headed cowbirds [*Molothrus ater* Boddaert]. On average, the SM was 29% lower ($\bar{x}$ = 8635, SE = 274.6) than the LM ($\bar{x}$ = 12,131, SE = 1530.8, $P < 0.001$). Mortality estimates by the SM were 21% lower ($\bar{x}$ = 7630, SE = 235.2, n = 12) under inclement than mild conditions ($\bar{x}$ = 9641, SE = 276.3, $P < 0.001$). Latitudinal difference between the states did not affect mortality estimates produced by the SM ($P > 0.65$). Unlike the LM, the SM used avian physiological and behavioral responses to environmental and meteorological conditions based on individual characteristics of the modeled blackbird species. It represents a scientifically rigorous and broad-scale approach that can be applied at all staging area baitings regardless of region or time-of-year. The SM will produce much lower mortality estimates compared to the LM when brown-headed cowbirds are the major species using staging area sites.

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1. Introduction

The avicide, DRC-1339 (3-chloro-4-methylaniline hydrochloride), has broad utility for managing several agricultural bird pests that damage both cereal grains and oilseed crops in the U.S. (Cummings et al., 2005; Linz et al., 2011; Wywialowski, 1996). It is highly toxic to blackbird (Icteridae) species listed in the U.S. Migratory Bird Depredation Permit (50 CFR 21.41), including red-winged blackbirds (*Agelaius phoeniceus* L), common grackles (*Quiscalus quiscula* L), and brown-headed cowbirds (*Molothrus ater* Boddaert) (Eisemann et al., 2003; Schafer, 1972; Schafer et al., 1977). Since 2008, the USDA has annually culled about 2 million blackbirds, with brown-headed cowbirds (BHCO) and red-winged blackbirds (RWBL) comprising the bulk of the cull (USDA, 2012). Most are taken during winter under the USEPA label, Compound DRC-1339 Concentrate – Staging Areas (USEPA Reg. No. 56228-30) in Missouri, Louisiana, and Texas (USDA, 2012).

Quantifying mortality through direct means such as carcass searches is impractical because DRC-1339 is a slow-acting toxin and poisoned birds are difficult to find (Homan et al., 2001; Kostecke et al., 2001). Currently, a linear model (LM) is used for estimating DRC-1339 mortality at staging areas. The data used in the LM were

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from analyses of blackbird esophageal contents collected during late winter at bait plots in Louisiana, Missouri, and Texas (Pipas et al., 2003). Because feeding behavior may vary by locality depending on food availability and seasonality, statistical inferences based on limited datasets may not be valid outside the time periods and geographical areas where the data were collected. Moreover, ephemeral factors such as ambient temperature and wind can influence avian feeding rates (Homan et al., 2011; Nagy et al., 1999), and failure to account for these influences can further restrict an LM's inferential scope. The sampling required to make a statistical model broadly applicable both regionally and temporally is often constrained by limited economic resources and personnel.

Mechanistic models, and hybrid variations having both statistical and mechanistic components (semi-mechanistic models [SM]), may overcome some of the regional and temporal limitations inherent in statistical models. For example, mechanistic models are independent of sampling vagaries, instead relying on mathematical formulae derived from first principles theory or knowledge of physical and biological states and processes (Hilborn and Mangel, 1997). We developed an SM that estimated daily metabolic energy demand by combining statistical distributions of avian morphology and physiology with the mechanistic processes of heat and energy transfer used in environmental biophysics (Campbell, 1977; Campbell and Norman, 1998; Monteith, 1973). Energy demand was used for estimating feeding rates, which in turn were combined with DRC-1339 toxicity regressions to calculate mortality probabilities (Glahn and Avery, 2001; Johnston et al., 2007, 2006; Nagy et al., 1999).

The LM currently used for estimating blackbird mortality at staging areas was constructed solely to fit an empirical dataset. By contrast, the SM was constructed with the intention of interpreting avian biophysical responses to environmental settings and the effect these responses may have on feeding rates at DRC-1339 bait sites, and ultimately mortality. The biophysical portion of the model has been tested, and it was found to accurately predict changes in daily energy demand and feeding rates of European starlings (*Sturnus vulgaris* L), with feeding rates related to changes in meteorological variables (Homan et al., 2011). An SM for estimating mortality of European starlings under the USEPA label, DRC-1339 Concentrate – Feedlots (EPA Reg. No. 56228-10) is already used by Wildlife Services (Homan et al., 2005). Here, we expand that model's basic premises to included DRC-1339 baiting at staging areas, where both different species and behaviors are expected to occur.

2. Methods

2.1. Semi-mechanistic model

We mechanistically simulated the abiotic environments at hypothetical bait sites in Missouri and Louisiana in 1-h segments over a 24-h period (Campbell, 1977; Campbell and Norman, 1998). The abiotic environment consisted of 1) solar angles of incidence; 2) direct, diffuse, and reflected irradiance; 3) ground and cloud emissivities; 4) molar density of air and specific heat; 5) water vapor pressure; 6) air turbulence; and 7) ambient temperature (see Homan et al., 2011). We created the biotic variables of the SM using interactions between the abiotic environment and avian morphological and physiological traits. The initial step in creating these biotic variables was a random drawing of individual masses from species- and sex-specific distributions normalized by Box–Mueller transformations (Dunning, 2007; Linz et al., 1995). From each mass, we calculated basal metabolism, body surface area, volume (prolate spheroid), and feather mass (Aschoff and Pohl, 1970; Kendeigh, 1970). Other biotic variables created from biophysical interactions with the abiotic environment included 1) exhalation temperature and vapor pressure, 2) evaporative heat loss from skin and respiratory tract, 3) Reynolds number, 4) convective and radiative heat losses from integument and body core, 5) resistances to convective and radiative heat losses, 6) absorbed radiation, 7) body surface emissivity, and 8) equivalent blackbody temperature (Campbell and Norman, 1998; Engel et al., 2006; Homan et al., 2011 [see for equations]; Wetmore, 1921). Using these variables, metabolic costs of thermoregulation were estimated from principles of heat and mass transfer between the bird and its physical environment (Bakken, 1976; Bakken and Gates, 1975; Calder and King, 1974; Robinson et al., 1976). The costs of basal metabolism, thermoregulation, and flight were combined to obtain an individual's daily metabolic demand (Homan et al., 2011; Torre-Bueno and LaRochelle, 1978).

The daily metabolic demand was converted to grams of rice using the gross caloric content of brown rice (Li et al., 2006). Gross caloric energy was converted to net energy by multiplying by species-specific digestive assimilation efficiencies (Shuman et al., 1989). For RWBL, the percentage of total daily energy demand obtainable from a single visit to a staging area bait site was randomly drawn from a Box–Mueller normalized distribution having a mean of 6% (SD = 1%). This value was derived from flight-pen studies that simulated staging area foraging behavior of RWBL on brown rice (Glahn and Avery, 2001). We calculated this value by using the net energy of the average amount of rice baits eaten per bird during one foraging bout and divided it by the estimate of total daily metabolic demand for RWBL held outdoors in Gainesville, Florida, during October and November 1987. We used the same foraging behavior distribution for BHCO, but modified it for common grackles (COGR) because of their comparatively larger body mass. For COGR, we used a mean of 4% (SD = 1%) of total daily energy demand in accordance with the asymptotic relationship in passeriform granivores between food-handling rates and body size (Keating et al., 1992). By linking foraging behavior at the staging area sites to percentage of estimated total daily energy demand, we have made the implicit assumption that energy requirements needed to support metabolism will largely determine feeding rates (Nagy et al., 1999). There are numerous empirical studies that have demonstrated that the quantity of food consumed is inversely correlated with decreasing ambient temperatures (Calder and King, 1974; Johnson and McTaggart-Cowan, 1975; Homan et al., 2011; Kendeigh, 1969). Thus, blackbirds will likely exploit DRC-1339 bait sites, feeding longer during periods of colder temperatures and inclement conditions, when their energy demands will be higher.

We converted the grams of eaten bait per bird at the bait site to bait particles by dividing by average particle mass of brown rice (0.019 g). Each particle was then randomly assigned a treated or untreated status befitting a 1:25 dilution ratio. The bird was assigned a probability of mortality based on a Lagrange linear interpolation commensurate with the milligrams of DRC-1339 ingested and categorized into Lethal Dose quartiles (Johnston et al., 2007). The standard deviation associated with each species' mean LD_{50} and response slopes were interpolated using probit analysis (Johnston et al., 2007). If the assigned probability of death equaled or exceeded a randomly drawn probability, the probability was enacted (i.e., death), otherwise the bird survived. The process as described above continued until all baits applied were consumed, iterating (after drawing anew from the mass distributions) through the environmental, biotic, foraging, and toxicity components of the model. Mortality was then quantified and returned as model output.

2.2. Linear model

The data used for the model were from esophagi of blackbirds collected in Louisiana, Missouri, and Texas during February and

March 2003 (Pipas et al., 2003). The collections were made at treated and untreated sites baited with brown rice. The average grams of baits in the esophagi of each species collected at the treated and untreated sites were used (see legend, Table 1), along with mortality probabilities that were calculated by using DRC-1339 residue analysis and colorimetric examinations of esophagi and gizzards of birds collected only at treated sites. The model estimated the number of birds visiting the bait site by dividing total grams of baits consumed by the average grams eaten per species per gender. The quotient was then multiplied by species- and sex-specific mortality rates associated with a 1:25 dilution ratio. For example, if 11.8 kg of brown rice were applied at a bait site and completely eaten by male BHCO, the model would predict that 89,369 BHCO ate baits (i.e., 11,793 g divided by the average consumption rate for male BHCO collected at the treated and untreated bait sites [0.132 g]). Of this group, 19,071 would be killed, which is calculated by multiplying the total number of birds that ate bait by the mortality probability for BHCO at a 1:25 dilution ratio (0.22). For a given gender, species, and bait amount, the LM will always return the same mortality value because only point estimates are used in the model.

2.3. Model comparisons and analysis

We compared the LM and SM for mortality estimates of RWBL, COGR, and BHCO. Estimates were made for males and females of each species. We compared the models using baiting scenarios that involved an application of 11.8 kg brown rice baits (2% DRC-1339) at a 1:25 dilution ratio (0.45 kg treated:11.3 kg untreated). The LM was run only one time per species per gender because estimates of mortality from the LM were not affected by changes in meteorological conditions or regionality, which were included among the various baiting scenarios. The SM was run twice per species per gender per state: once using the average coldest day (min. temp. −8 °C, max. temp. 0.5 °C) in Cape Girardeau, Missouri, and once using the average warmest day (min. temp. 19 °C, max. temp. 25 °C) in Lafayette, Louisiana, during January 2012. For the coldest day, we used wind speeds >32 km h^{-1} and 100% stratus cloud cover. For the warmest day, we used clear skies and no wind. Thus, when comparing differences by meteorological condition, we created both the worst- and best case meteorological scenarios. The SM model will yield mortality estimates in between these two meteorological extremes in moderate scenarios. We also conducted comparisons within the SM for differences in mortality based on regionality. The baits sites were 800 km apart latitudinally (Cape Girardeau [37.38N, −89.72W], Lafayette [30.22N, −92.01W]). We used one-way ANOVA to test for differences ($\alpha = 0.05$) in mortality between models.

3. Results

On average for all species and sexes combined, the SM estimates of mortality were 29% lower ($\bar{x} = 8635$, SE = 274.6, $n = 24$) than the LM ($\bar{x} = 12{,}131$, SE = 1530.8, $n = 6$, $F_{1,\ 28} = 14.7$, $P < 0.001$). Compared to mortality estimated by the LM, the SM ranged from 5% higher (male COGR: 8821 *vs.* 8381) to 59% lower (male BHCO: 7866 *vs.* 19,071) (Table 1). For the LM, overall mortality was higher for males ($\bar{x} = 12{,}725$, SE = 3244.1, $n = 3$) than females ($\bar{x} = 11{,}536$, SE = 2747.1, $n = 3$), whereas the SM produced higher estimates for females ($\bar{x} = 9247$, SE = 361.0, $n = 12$) than males ($\bar{x} = 8024$, SE = 342.3, $n = 12$). The number of rice grains eaten per bird differed between the two models, with the SM predicting over twice the amount ($\bar{x} = 49$, SE = 2.8, $n = 24$) of the LM ($\bar{x} = 22$, SE = 5.6, $n = 6$). As a result, mortality rates (i.e., killed ÷ visited) predicted by the SM ($\bar{x} = 0.66$, SE = 0.02, $n = 24$) were always greater than the LM ($\bar{x} = 0.32$, SE = 0.08, $n = 6$).

Table 1
Comparisons of mortality estimates (in 1000's) between linear (LM)[a] and semi-mechanistic (SM)[b] models for three blackbird species following a mock staging area baiting using 2% DRC-1339 brown rice baits at a 1:25 dilution and 11.8 kg eaten. The SM used the coldest average day (C) in Cape Girardeau, MO, and warmest average day (W) in Lafayette, LA, during January 2012.

Sex	Model	State	Blackbird species													
			RWBL					BHCO					COGR			
			Mortality	Visited	Mortality rate[c]	Baits eaten[d]	Model ratio[e]	Mortality	Visited	Mortality rate	Baits eaten	Model ratio	Mortality	Visited	Mortality rate	Baits eaten	Model ratio
Male	LM		10.7	25.5	0.42	24		19.1	89.4	0.21	7		8.4	14.1	0.59	44	
	SM-C	LA	6.7	10.2	0.66	61	0.38	7.9	11.6	0.68	54	0.58	6.7	8.1	0.83	77	0.20
	SM-W	LA	8.4	16.0	0.53	39	0.22	10.1	18.2	0.55	34	0.47	8.8	12.5	0.71	50	−0.05
	SM-C	MO	6.7	10.1	0.67	62	0.37	7.9	11.5	0.69	54	0.59	6.6	8.0	0.83	78	0.21
	SM-W	MO	8.2	15.0	0.55	41	0.23	9.7	17.1	0.57	36	0.49	8.6	11.7	0.73	53	−0.02
Female	LM		11.1	38.3	0.29	16		13.3	59.6	0.22	10		10.2	20.6	0.49	30	
	SM-C	LA	8.3	12.6	0.66	49	0.25	8.8	13.0	0.67	48	0.24	7.5	9.1	0.82	68	0.32
	SM-W	LA	10.6	19.8	0.54	31	0.04	11.0	20.4	0.54	30	0.12	9.7	14.2	0.68	44	0.06
	SM-C	MO	8.4	12.4	0.67	50	0.25	8.7	12.8	0.68	48	0.24	7.4	9.0	0.82	69	0.33
	SM-W	MO	10.3	18.7	0.55	33	0.07	10.7	19.3	0.56	32	0.13	9.5	13.3	0.71	46	0.09

[a] Baits eaten and mortality rate variables are as follows: M & F RWBL = 0.462 g/0.42 & 0.308 g/0.29, M & F COGR = 0.836 g/0.66 & 0.572 g/0.55, and M & F BHCO = 0.132 g/0.22 & 0.198 g/0.23.
[b] C = coldest day: min. temp. −8 °C, max. temp. 0.5 °C; wind speed >32 km h^{-1}, and 100% coverage of status clouds; W = min. temp. 19 °C, max. temp. 25 °C; no wind, and clear skies.
[c] Mortality divided by number of birds that visited the bait site.
[d] Average grains eaten per individual. There are 620,705 brown rice grains in 11.8 kg @ 0.019 g/grain.
[e] Proportional difference in estimates between the LM and the SM.

Mortality was lower for the SM under cold weather scenarios ($\bar{x} = 7630$, SE = 235.2, $n = 12$) compared to warm weather scenarios ($\bar{x} = 9641$, SE = 276.3, $n = 12$, $F_{1,\ 22} = 30.7$, $P < 0.001$); whereas latitudinal difference between Lafayette and Cape Girardeau did not affect mortality (P's > 0.65). Lastly, mortality was always greater in Louisiana than Missouri under like weather scenarios, although the differences were small (cold: 7648 *vs.* 7612; warm: 9772 *vs.* 9509). These results are consistent with the deterministic behavior of SM, which accounts for solar angles of incidence and the concomitant changes in radiant load.

4. Discussion

The average ingestion rate of 49 grains per feeding bout predicted by the SM represents about 2 min of foraging time at the bait sites using a feeding rate of 24 baits per minute for brown rice (Glahn and Avery, 2001). By comparison, the LM predicted that birds spent less than a minute feeding at the bait sites, much shorter than the 2.25-min average bout found by Glahn and Avery (2001). This is a large difference between the two models and directly affected the amount of mortality estimated by them. The SM was lower in its estimates because higher feeding rates will always cause lower mortality rates (i.e., less DRC-1339 available for other birds coming to the bait site). The shorter feeding times per bout estimated by the LM could have perhaps occurred if foraging birds had become aware of the presence or approach of collectors, also using only esophageal contents and not including gizzard contents may have partially contributed to the lower feeding rates.

Some of the estimates generated by the LM were questionable. For example, male BHCO are about 25% larger than their female counterparts, yet males consumed fewer rice grains (7 *vs.* 10 grains). The prediction by the LM implies that female BHCO either spent more time feeding at bait sites or handled brown rice grains more efficiently than males; however, there are no morphological or biological reasons that should lead to these conclusions. Moreover, it challenges the results from food-habits studies on BHCO and the documented relationship between food-handling times and morphology in granivorous birds (Dolbeer and Smith, 1985; Keating et al., 1992). By comparison, the LM predicted that males ate more rice than females for the other two species used in the model. The anomalous result for BHCO may have been caused by insufficient sample sizes combined with large variances commonly associated with field sampling. Regardless, the very large mortality of male BHCO predicted by the LM (>19,000) strongly influenced the difference in outcomes between the models. On the other hand, collections were adequate for male and female RWBL (>200 birds each), yet even for this species, estimates of mortality between the LM and SM models diverged considerably. We speculate that the sampling conducted to obtain data for the LM, which involved shotgun collections, may have negatively biased foraging times and interfered with the normal, more prolonged feeding times of birds typically using staging area bait sites.

It could be argued that the SM is also inaccurate. However, use of deterministic–mechanistic modeling for quantifying avian bioenergetics is well established, and we feel confident in the SM's abilities to accurately predict daily energetic demand (Bakken and Gates, 1975; Calder and King, 1974; Campbell, 1977; Kendeigh et al., 1977; Robinson et al., 1976). We also believe that the laboratory toxicity data and statistical analyses of DRC-1339 mortality can be used reliably in the SM (Eisemann et al., 2003; Homan et al., 2005; Johnston et al., 2006, 2007). Perhaps the most tenuous assumption in the SM was in the setting of the maximum capacities of obtainable daily energy. Admittedly, data are sparse on foraging behavior at staging areas, and we relied solely on Glahn and Avery (2001) for depiction of staging area foraging behavior. However, the Glahn and Avery study used several replications and we incorporated the variance of these into the foraging component of the SM.

A major disadvantage of using LM to quantify DRC-1339 mortality is the difficulty in designing effective sampling schemes to overcome problems of using field collections to determine feeding habits (Homan et al., 1994). The large difference in mortality between male BHCO and RWBL in the LM is indicative of the challenges of using field sampling at bait plots to estimate DRC-1339 mortality. For example, the amount of baits consumed was 7 for BHCO and 24 for RWBL. Although differences in body sizes and mandible sizes between the two species will obviously affect food-handling capabilities, it should not be to the degree predicted by the LM (Keating et al., 1992). The SM, on the other hand, averaged 45 and 51 baits for male BHCO and RWBL, respectively. It is the quantitative nature of mechanistic models to be more precise in their estimates, and certainly there is less intra-model variation in the SM than was observed in the LM.

5. Conclusions and management implications

Integrating avian bioenergetics (through biophysical interactions with the environment) with DRC-1339 toxicity regressions, mortality probabilities, and simulations of foraging behavior should provide reliable quantification of mortality. The SM should overcome some of the regional and temporal limitations of LM, which often must rely on only a few samples drawn from only a few locales, when the statistical population itself may have considerable variation regionally and temporally. We believe that the SM represents a more rigorous and scientifically justifiable approach for estimating DRC-1339 mortality (NAS, 2001). It is broad-scaled and can be applied at all staging area bait sites regardless of region or time-of-year. Use of the SM should result in an average reduction of mortality estimates somewhat greater than 29% because RWBL and BHCO are the two major species being taken under the Staging Areas label. The SM will produce much lower estimates compared to the LM when BHCO are the major species using staging area sites.

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