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Proceedings of the Vertebrate Pest Conference

Title

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Journal

Proceedings of the Vertebrate Pest Conference, 24(24)

ISSN

0507-6773

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Publication Date

2010

DOI

10.5070/V424110700

Anticoagulant Residual Concentration and Poisoning in Birds Following a Large-Scale Aerial Broadcast of 25-ppm Brodifacoum Bait for Rat Eradication on Rat Island, Alaska

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ABSTRACT: To eradicate invasive Norway rats, an aerial broadcast of the rodenticide Brodifacoum-25W Conservation was conducted on 2,777-ha Rat Island, within the Aleutian Islands Unit of Alaska Maritime National Wildlife Refuge, between 29 September and 5 October 2008. During subsequent visits to Rat Island (in spring and fall 2009) to check for evidence of remaining rats and to look for evidence of nontarget mortality, personnel found an unexpectedly high number of dead birds: more than 420 carcasses, mostly glaucous-winged gulls and bald eagles, but also included 24 other species. Some carcasses had tissue suitable for analysis and were collected. Seventy bird carcasses were necropsied and cause of death was determined for 50 birds; 45 died of brodifacoum toxicosis. Necropsy determined almost all gulls and eagles had extensive hemorrhaging, consistent with brodifacoum poisoning. All eagles and all but 1 gull tested positive for brodifacoum residues. Positive tests for brodifacoum also were recorded for single specimens of emperor goose, northern fulmar, pelagic cormorant, peregrine falcon, rock sandpiper, and gray-crowned rosy finch. Two Lapland longspurs tested positive for exposure to brodifacoum. Nontarget bird mortality from brodifacoum exposure at Rat Island was higher than predicted in the Environmental Assessment.

KEY WORDS: aerial broadcast, Alaska, Aleutian Islands, bird deaths, brodifacoum, ecosystem restoration, eradication, invasive, nontarget poisoning, Norway rat, pesticides, Rat Island, *Rattus norvegicus*, rodenticides, secondary poisoning

Proc. 24th Vertebr. Pest Conf. (R. M. Timm and K. A. Fagerstone, Eds.)
Published at Univ. of Calif., Davis. 2010. Pp. 153-160.

INTRODUCTION

Rat Island is one of 10 large Aleutian Islands that were invaded by Norway rats (*Rattus norvegicus*) either during Alaska's Russian period, during World War II, or soon after the war. Norway rats became established on Rat Island about 1780 when a Japanese ship went aground (Black 1984), and subsequently on its surrounding smaller islands within dispersal distance.

Like most of the other islands within the Aleutians, Rat Island became part of the Aleutian Islands National Wildlife Refuge in 1913, eventually becoming part of the larger Alaska Maritime National Wildlife Refuge. One of the purposes of the Refuge is to try to restore native island ecosystems by removing invasive species. Arctic foxes (*Vulpes lagopus*) were introduced on most Refuge islands for fur production prior to World War II (Bailey 1993). Foxes and rats reduced native biodiversity on the islands through predation on native species, and removal of foxes by the Refuge began soon after the end of WWII (Bailey 1993). Arctic foxes were introduced on Rat Island in 1922 and the U.S. Fish and Wildlife Service (FWS) eradicated foxes on Rat Island in 1984 (Hanson et al. 1984, Bailey 1993). Ecosystem recovery began as a result of fox removal, and some bird species did increase, e.g., Aleutian cackling goose (*Branta hutchinsii leucopareia*), common eider (*Somateria mollissima v-nigra*), glaucous-winged gull (*Larus glaucescens*), and black oystercatchers (*Haematopus bachmani*). Nevertheless, complete restoration of some highly disturbance-sensitive bird fauna remained limited by the presence of Norway rats.

Elsewhere, the impacts of invasive rats on some islands are well-documented (Moors and Atkinson 1984, Courchamp et al. 2003, Jones et al. 2008). Rodenticides have been used to remove Norway rats on a number of islands around the world including islands up to 11,300 ha in size (Towns and Broome 2003). In 2006, FWS partnered with The Nature Conservancy and Island Conservation (IC) to develop and implement a plan to eradicate rats from Rat Island, a relatively large island for rat eradication, by twice aerially broadcasting bait containing the anticoagulant rodenticide brodifacoum over most of the island, and by hand-broadcast around the island's lakes. All bait application occurred in 7 consecutive days, beginning on 29 September and ending 5 October 2008 (Buckelew et al. 2009). Fifty-one tons of rodenticide bait, containing 25 ppm of the anticoagulant brodifacoum, was broadcast over 2,777 ha (which included Rat Island and other small islands just offshore).

Based on studies indicating rat densities were higher in coastal areas, the target application rate was twice as great along the 110-m coastal fringe of the island as on inland areas. Bait was broadcast in overlapping aerial swaths, except for a single application by hand broadcast near lake systems. Freshwater lakes on Rat Island occur in clusters, and bait was hand broadcast in these areas to minimize pellets falling into these water bodies. Bait was aerially broadcast throughout the inland area, which included 200 streams. All areas received 2 broadcasts with 2 - 4 days between, and aerial or hand-broadcast applications occurred every day somewhere on the island. On the seventh and final day of baiting, aerial broadcast

targeted steep coastal cliffs where there was the highest perceived risk of rats surviving the eradication effort. The cumulative application rate within the 7-day period was as high as 32.7 kg/ha in some coastal cliff areas, 19.0 kg/ha on inland cliff areas, and 8.0 kg/ha in lake areas.

Radio telemetry was not used at Rat Island to estimate survival of rats, but all dead rats opportunistically collected during the eradication operation were examined. A total of 23 dead or dying rats were examined on the island, and all but one showed evidence of anticoagulant poisoning. Although no nontarget mortality was noticed during the 7 days of bait application, no post-application monitoring was conducted because the camp, helicopters, ship, and personnel were demobilized the day after bait application was completed.

Seven months later, an IC crew returned to Rat Island in 26 May 2009 for 3 weeks of study to look for signs that rats remained and any evidence that native birds were beginning to show early signs of recovery. The crew found no sign of rats, but they did discover an unexpectedly large number of dead birds, particularly glaucous-winged gulls but also bald eagles (*Haliaeetus leucocephalus*) and a least 24 other species. Nontarget bird mortality was higher than expected in the eradication decision-making and planning process, and not predicted in the Environmental Assessment for Rat Island (USFWS 2007). This paper summarizes the results of necropsies and laboratory tests for anticoagulant residues for some bird carcasses, and it briefly describes feeding habits of those species that were found to have been exposed to brodifacoum.

METHODS

Carcass Surveys and Collection

Bucklelew et al. (2010) described the methods used for carcass searches on Rat Island, which included searches along beaches and opportunistic finds in the island's interior. Initially, some bird carcasses were buried on Rat Island after they were examined and tissue samples were collected. Nevertheless, when it became apparent that more than just a few gulls were involved, specimens were collected and eventually transferred to freezers on the M/V Tiglax. Camp personnel departed Rat Island on 18 June, but due the nontarget mortality recorded that spring, additional surveys were conducted on 2 different days in August for further collections. Some gull carcasses buried in June, particularly those buried in sand or placed under driftwood, were found again during August surveys, and we attempted to reconcile tallies to avoid double counting.

Necropsy and Residue Testing

Initially, 8 gull carcasses collected 26 May 2009 on Rat Island were shipped to the U.S. Geological Survey, National Wildlife Health Center (NWHC) in Madison, Wisconsin. Although brodifacoum poisoning was suspected, pathologists conducted a complete necropsy examination to consider other possible causes of death. Cause of death was determined by necropsy of carcasses in varying states of decomposition, and if available, chemical residue analysis of tissue or stomach contents. In some cases, residue analysis was possible and con-

ducted, but the state of the carcass prevented definitive determination of cause of death.

When anticoagulant rodenticide toxicity is suspected as the cause of death, the NWHC can send tissue samples to the Diagnostic Center for Population and Animal Health (DCPAH), Lansing, Michigan, for anticoagulant screening. Probable anticoagulant poisoning can be detected with necropsy, and if tissues are present and not too degraded, residue analysis can confirm specific anticoagulants, e.g. brodifacoum. Liver tissue is preferred for anticoagulant detection and residue analysis because anticoagulant compounds primarily bind to vitamin K receptors within liver cells (Record and Marsh 1988, Eason and Wickstrom 2001, Fisher et al. 2003).

The DCPAH uses a High Performance Liquid Chromatography (HPLC) method to identify and quantify anticoagulant rodenticides from tissues and other samples (A. Lehner, DCPAH, pers. commun.). The system can detect brodifacoum, bromadiolone, difenacoum, chlorophacinone, difethialone, diphacinone, warfarin, coumachlor, coumafuryl, and coumatetralyl (Reynolds 1980, Braselton et al. 1992, Yamini et al. 1995). The test is highly sensitive, yet samples may test negative even when post-mortem evidence indicates anticoagulant poisoning. The minimum detection level for brodifacoum in the Rat Island samples was ≥ 0.002 ppm.

After necropsy and residue tests of the initial specimens submitted confirmed that nontarget poisoning had occurred on Rat Island, one of the authors (KBH, a board-certified wildlife pathologist) conducted necropsies on selected bird carcasses from Rat Island and sent tissue samples for anticoagulant residue analysis to DCHAP (to maintain comparability of results with the initial 8 specimens tested). We selected carcasses for necropsy based on species and level of degradation. Most eagle carcasses collected with liver tissue intact were examined, and gulls less degraded than others were tested for brodifacoum exposure. Few carcasses of other species were actually collected, and some of these were necropsied to broaden the range of trophic levels of species examined and tested for residues.

Liver samples from 33 bird specimens (18 bald eagles, 8 glaucous-winged gulls, and 8 birds of 8 additional species) were submitted for anticoagulant screening including brodifacoum residues. Stomach contents were submitted for residue testing from 4 gulls, 2 eagles, 1 gray-crowned rosy finch (*Leucosticte tephrocotis*), and 1 Lapland longspur (*Calcarius lapponicus*).

Additional testing was conducted in the search for contributing factors to mortality besides anticoagulant poisoning. Livers from 3 eagles that showed marginal lesions, or were under-weight, were screened for 21 heavy metals by DCPAH along with 1 emperor goose (*Chen canagica*) liver.

Stomach contents, gastro-intestinal contents, or cloacal contents were submitted to the Northwest Fisheries Science Center, Seattle, Washington for Harmful Algal Bloom (HABs) testing. These samples were screened for domoic acid and a panel of saxitoxins using an enzyme-linked immunosorbent assay (ELISA). Domoic acid detection used Biosense ELISA (3-5-10 and 3-15-10) and the saxitoxins test was by Abraxis ELISA (3-10-10).

Positive samples were further analyzed by liquid chromatography / mass spectroscopy. Some samples submitted were only large enough to be tested for one type of toxin.

Cloacal and choanal swabs were taken from relatively fresh birds tested by the National Veterinary Services Laboratories or the Alaska Environmental Health Laboratory for RT-PCR detection of avian influenza and Newcastle disease virus.

The IC crew collected 24 fresh water and 20 soil samples in June 2009. Freshwater and soil sampling methods are described in Buckelew et al. (2010). Eight water samples and 6 soil samples were sent to the University of California at Davis and tested for the presence of brodifacoum. The reporting limit for brodifacoum in water is 1 ppb, and 0.2 ppm in soil.

RESULTS

Carcass Surveys and Collection

During a 3-week period in late May and early June 2009, 7 persons counted 294 carcasses on Rat Island. During two 1-day visits in August, 129 carcasses were documented, primarily along the coast. As indicated above, some carcasses found in June but not collected were also found in August. After accounting for carcasses seen during both periods, at least 423 carcasses were found on Rat Island in June and August 2009 including 320 glaucous-winged gulls (75%) and 46 bald eagles (11%). Many carcasses were in relatively advanced stages of decomposition. Besides gulls and eagles, the other 57 carcasses (14%) found were composed of 1 to 7 individuals of at least 24 other species (Buckelew et al. 2009).

Necropsy and Residue Analysis for Rodenticides

Although a pathologist examined 70 carcasses of 12 species, cause of death was determined for 50 carcasses (Table 1) and could not be determined for 20 carcasses, typically because of their degraded state. Symptoms such

as hemorrhaging and pulmonary edema that are consistent with anticoagulant poisoning indicated brodifacoum toxicosis was the probable cause of death in 64% (45 of 70) of the carcasses examined, and 90% (45 of 50) of cases where cause of death could be determined (Burek 2010). Low to very high levels of brodifacoum residues were found in liver samples from 97% (32 of 33) of birds tested (Table 1). Stomach contents were examined from 8 carcasses and all tested positive for brodifacoum residues. Details of these analyses are provided below for various species.

Other potential causes of death, in addition to anticoagulant poisoning, were determined for 5 birds examined: 2 gulls, 1 northern fulmar (*Fulmarus glacialis*), 1 pelagic cormorant (*Phalacrocorax pelagicus*), and 1 emperor goose. However, 1 of the 2 gulls, the fulmar, cormorant, and goose contained brodifacoum residues in their livers.

One each harlequin duck (*Histrionicus histrionicus*), parakeet auklet (*Aethia psittacula*) and snow bunting (*Plectophanax nivalis*) was examined, but cause of death was not determined.

Gulls

Necropsies indicated almost all gulls examined had extensive hemorrhaging, consistent with anticoagulant poisoning. Six of 7 gull livers tested were positive for brodifacoum, 4 at very high levels (0.709 - 4.189 ppm). All 4 stomachs tested (3 from gulls without testable livers) contained brodifacoum residue with levels ranging from 0.230 - 2.338 ppm. One gull liver also tested positive for bromadiolone and 2 tested positive for difenacoum.

Eagles

All 21 eagle carcasses necropsied were highly autolyzed (destruction of tissues or cells by the action of substances, such as enzymes, that are produced within a

Table 1. Results of necropsy and residue analysis of bird carcasses from Rat Island.

Species	# Necropsies	# Brodif. Residue / # Tested	CoD Anticoagulant Poisoning ^a	CoD Other	CoD Unknown
glaucous-winged gull	35	9/10	24	2	9
bald eagle	21	18/18	18	0	3
emperor goose	1	1/1	0	1	0
northern fulmar	1	1/1	0	1	0
pelagic cormorant	1	1/1	0	1	0
rock sandpiper	2	1/1	0	0	2
peregrine falcon	1	1/1	1	0	0
Lapland longspur	2	2/2	1	0	1
gray-crowned rosy finch	2	1/1	1	0	1
harlequin duck	1	NT ^b	0	0	1
parakeet auklet	1	NT	0	0	1
snow bunting	2	NT	0	0	2
Total	70	35/36	45	5	20

CoD = Cause of death

^a Symptoms consistent with anticoagulant poisoning

^b NT = Not tested

carcass) and most had muscle pallor, pulmonary edema, and possible hemorrhage. Many were in poor body condition. Liver samples submitted from 18 eagles tested positive for low to high (0.429 - 2.599 ppm) levels of brodifacoum. Also, brodifacoum was present (0.304 ppm, 0.338 ppm) in stomach content samples submitted from 2 eagles. A small amount of difenacoum also was detected in the liver of 1 eagle.

Other Species

Necropsies were conducted on 14 other bird carcasses of 10 species. Liver tissue samples were submitted from 7 of these, and residue tests revealed low to high levels of brodifacoum were present in all. Brodifacoum residue levels, high enough to suggest poisoning as the cause of death, were found in 1 peregrine falcon (*Falco peregrinus*) (1.226 ppm), 2 Lapland longspurs (0.560 ppm, 2.989 ppm), and 1 gray-crowned rosy finch (1.219 ppm). One of the longspurs (0.141 ppm) and the rosy finch (trace amounts) also had brodifacoum residues in their stomachs. Brodifacoum residues were found in the livers of an emperor goose (0.027 ppm), northern fulmar (0.057 ppm), pelagic cormorant (0.044 ppm), and rock sandpiper (*Calidris ptilocnemis*) (0.043 ppm). The goose had esophageal and ventricular impaction, the fulmar possibly died of starvation, the cormorant was predated, and cause of death was not determined for the rock sandpiper.

Liver tissue was tested from 1 rat found on Rat Island in 2009, and showed an extremely high level of brodifacoum residue (19.328 ppm). Stomach contents also tested positive for brodifacoum (3.280 ppm) and difenacoum (0.35 ppm).

Analysis of Heavy Metals and Other Toxins

Heavy Metals

Liver tissue from 1 glaucous-winged gull was screened for heavy metals and tested higher than normal for cadmium, but not at a toxic level. This gull was also the only specimen tested that did not have some level of brodifacoum either in its liver or stomach. Three eagle livers were submitted for toxic metals but were found negative or within their normal range. In all 3 eagles tested, however, the amount of calcium was high.

Harmful Algal Blooms

Domoic acid and saxitoxin are toxins produced by harmful algal blooms. Twenty-one samples from bird carcasses collected on Rat Island suitable for testing for domoic acid were submitted, and only 2 birds (a sub-adult eagle and an adult glaucous-winged gull) were positive at very low levels. All 27 samples submitted for saxitoxin were below detectable limits.

Avian Virus

None of the birds tested were positive for avian influenza, and 1 gull was positive for Newcastle disease.

Water, Soil Residue

No brodifacoum residue was detected in the water ($n = 8$) or soil ($n = 6$) samples tested in 2009.

DISCUSSION

Carcass Surveys and Collection

Not all affected birds died on Rat Island, and not all carcasses present on Rat Island were found; also not all those discovered on Rat Island in 2009 were collected. In addition, necropsies were not performed on all carcasses collected. The absolute number of bird carcasses deposited on and around Rat Island resulting from the bait application or other causes is underestimated by this sample partly because of the length of time between bait application in October 2008 and the first surveys of beaches for carcasses on Rat Island 8 months later.

When avian mortality occurs around islands, carcasses may be deposited along the shoreline and sometimes wash out to sea, only to become deposited elsewhere along a different shore or a different island. Some unknown amount of exposed birds likely flew to sea or other islands before succumbing to the toxicant because of the delayed effects of anticoagulants. Typical bird carcass deposition rates from natural mortality for Rat Island are unknown. Therefore, we do not know what proportion of dead bird carcasses on Rat Island we found after bait application.

Necropsy and Residue Analysis for Rodenticides

Some specimens collected on Rat Island appeared to have died more recently than the time of bait application, but many bird carcasses examined by the pathologists were in an advanced state of decomposition or had tissues removed in the field, so that it was not possible to determine cause of death conclusively. However, it is possible to detect brodifacoum residue in birds and mammals for more than a year after exposure (Eason and Wickstrom 2001), long after pellets are expected to last in the field. For instance, brodifacoum was detected in Northwestern crows (*Corvus caurinus*) 9 months after baiting with brodifacoum on Lucy Island (Howald 1997).

Of the 50 carcasses, mostly gulls and eagles, where cause of death could be determined, nearly all died from brodifacoum poisoning, and individuals of 7 other species were at least exposed. Species for which mortality was caused by anticoagulant toxicosis include glaucous-winged gull, bald eagle, peregrine falcon, Lapland longspur and gray-crowned rosy finch. Specimens for which lower levels of brodifacoum residues were detected include rock sandpiper, emperor goose, pelagic cormorant, and northern fulmar. Nontarget bird exposure is documented in other aerial broadcasts of brodifacoum bait (Armstrong and Ewen 2000, Armstrong et al. 2001, Eason and Spurr 1995, Davidson and Armstrong 2002, Hoare and Hare 2006, Howald et al. 2009).

Documented primary and secondary exposures of nontarget species to brodifacoum in New Zealand include native birds such as southern black-backed gull (*Larus dominicanus*) (Fisher 2009). Livers tested from 4 of the 8 gulls from Rat Island had higher levels (3.463-4.189 ppm) of brodifacoum residues than documented for any species of gull reported previously (Fisher 2009).

Stone et al. (1999) documented brodifacoum poisoning of raptors, including golden eagles (*Aquila chrysaetos*). Previously, the highest levels of brodifacoum

cum liver residue documented in a raptor outside of captive trials were 1.6 ppm (Stone et al. 1999) and 1.67 ppm (Gray et al. 1992), as reported in Fisher (2009). Four bald eagles tested from Rat Island exceeded these levels (2.080 - 2.599 ppm). Brodifacoum residue levels as low as 0.03 ppm in the liver have been associated with mortality in raptors (Stone et al. 2003). The lowest detected level of brodifacoum in liver tissue tested from Rat Island bald eagles carcasses was 0.055 ppm.

All testable carcasses of land birds found after aerial brodifacoum bait application on Anacapa Island likely died from brodifacoum exposure (Howald et al. 2005).

Exposure Pathways

Descriptions of brodifacoum and its effects on nontarget species can be found in Borst and Counotte (2002), Booth et al. (2001), Dowding et al. (1999), DuVall et al. (1989), Eason et al. (1999), Eason et al. (2002), Erickson and Urban (2004), Godfrey (1986), Murphy et al. (1998), Ogilvie et al. (1997), Gerlach and Florens (2000), and Spurr and Drew (1999).

Species feeding behavior and diet can help explain whether primary or secondary exposure was possible for birds found on Rat Island with brodifacoum residues. For instance, because a rat can continue to consume bait until its death 4 to 10 days later (Hooker and Innes 1995), it can consume many times a lethal dose. These rat carcasses 'super-loaded' with brodifacoum can pose a risk to nontarget scavengers such as eagles that are unlikely to ingest bait (Cox and Smith 1992). Of the 9 species for which we have conclusive evidence of brodifacoum exposure on Rat Island, 3 species (gull, longspur, and rosy finch) could have ingested bait directly and all 9 species could have ingested brodifacoum indirectly by preying on or scavenging organisms that consumed the bait.

Glaucous-winged gulls are opportunistic feeders (Verbeek 1993), preying on other birds, small mammals, fish, and invertebrates, or scavenging on a wide range of items including garbage and fish processing waste in the Aleutian Islands (Gibson and Byrd 2007). Gulls are probably present on Rat Island year-round (Gibson and Byrd 2007). During the baiting operation in 2008, glaucous-winged gulls were common on beaches and offshore rocks (Buckelew et al. 2009). Most gull mortality could have occurred soon after bait application, but potentially scavenging could have occurred if contaminated carcasses were uncovered from snow in spring 2009. During a study in the central Aleutians in 2006 (Buckelew et al. 2007), Brodifacoum 25W Conservation bait was broadcast on 5 small islands. Forty percent of the monitored rats died above ground and 60% died under cover. Dowding et al. (1999), Howald et al. (2009), Stone et al. (1999), Williams et al. (1986), and others have reported mortality of gulls after brodifacoum operations. Based on their foraging habits, gulls might ingest bait directly and/or prey upon and/or scavenge rats and/or birds that ingested bait.

Like gulls, bald eagles are opportunistic predators and scavengers (Buehler 2000). In the Aleutians, eagles prey particularly on seabirds, waterfowl, and fish, but also prey on introduced mammals and scavenge carrion and/or

garbage (Sherrod et al. 1976). Eagles are year-round residents in the Aleutians, but there is inter-island movement associated with preying or scavenging opportunities (e.g., salmon spawning streams during fall, island landfills and fish processing facilities during winter) (Gibson and Byrd 2007). Sherrod et al. (1976) recorded eagles preying on Norway rats on Amchitka Island, only 23 km to the southeast of Rat Island. Few eagles were observed on Rat Island during the bait application (Buckelew et al. 2009), and yet by May 2009 it became readily apparent many eagles had been exposed to brodifacoum. Howald et al. (1999) concluded that the use of brodifacoum for rat eradication on seabird islands poses a clear risk of secondary poisoning to avian scavengers, including bald eagles. Eagles are more likely to scavenge or prey on exposed gulls and other birds than forage on grain-based pellets.

Peregrine falcons in the Aleutians prey on live medium-sized birds, and occasionally hunt small mammals and insects (White et al. 2002). The species is a year-round resident in the Aleutians (Gibson and Byrd 2007). As top predators in food webs, they are good indicators of biological magnification of chemicals because they can accumulate persistent pesticides by preying on other birds that are exposed (White et al. 1973).

Lapland longspurs and gray-crowned rosy finches are candidates for primary exposure and also at risk of secondary poisoning by consuming insects or other invertebrates that consumed bait. Lapland longspurs are known for eating waste grain in agricultural fields and seeds during migration, but they also feed on insects when feeding young (Hussell and Montgomerie 2002). Longspurs are absent from the Aleutian Islands during winter, and most had departed Rat Island by the time of the rodenticide broadcast (Buckelew et al. 2009). The species typically returns to the Aleutians in May to nest (Gibson and Byrd 2007). Gray-crowned rosy finches are resident in the Aleutians and feed on seeds during winter and insects, especially insect larvae, during summer (MacDougall-Shackleton et al. 2000). Stejneger (1885) reported larval beetles (*Coleoptera*), leaves, buds, and seeds in the gut of Aleutian rosy finches. Insects that scavenge on rat carcasses can be a source for brodifacoum exposure to insectivorous birds (Howald et al. 2009). Longspurs or rosy finches feeding on insects after bait application could be at risk by secondary exposure. Secondary exposure was demonstrated for a similar passerine, the song sparrow (*Melospiza melodia*), during the Langara Island rat eradication (Howald 1997).

Rock sandpipers are resident year-round in the Aleutian Islands (Gibson and Byrd 2007). They eat adult and larval insects on the tundra, and other invertebrates, especially marine clams and snails in the intertidal zone where they congregate in fall (Gill et al. 2002), but they are not known to eat grain or grain pellets such as those broadcast on Rat Island. However, invertebrates, including snails and earthworms (Booth et al. 2003), insects (Ogilvie et al. 1997, Craddock 2003, Eason and Spurr 1995), and crabs (Pain et al. 2000) can pose a potential secondary and tertiary risk of brodifacoum poisoning to birds (Howald 1997, Fisher 2009).

Dowding et al. (2006) described how high mortality of New Zealand dotterels (*Charadrius obscurus*) occurred 9 months later from secondary exposure to brodifacoum bait via invertebrates.

Emperor geese winter in the Aleutian Islands (Gibson and Byrd 2007), where they typically feed in the intertidal zone on plants like sea lettuce but may also ingest mollusks and crustaceans (Petersen et al. 1994). It is unclear how a coastal-dwelling emperor goose might encounter the rodenticide, except via secondary exposure.

Pelagic cormorants feed in nearshore marine waters consuming fish and marine invertebrates (Hobson 1997). They roost on offshore rocks or sea cliffs. Cormorants are not known to be scavengers, and it is possible that exposure to brodifacoum occurred through the marine food web. Three species of marine fish were observed to eat similar brodifacoum bait in aquarium trials and had brodifacoum residue in their livers (Empson and Miskelly 1999).

Northern fulmars feed in the open ocean on fish and crustaceans, but they also will consume marine fish waste at sea and are known for following fishing vessels (Hatch and Nettleship 1998). Fulmars also scavenge dead floating birds, and it is possible that a fulmar could have fed on dead gulls or other birds that died at sea or their carcasses that washed away from the coast.

Presence of Other Chemicals or Disease

Five samples tested had low levels of difenacoum: stomachs of 2 gulls, 1 Lapland longspur and 1 rat, and the liver of 1 eagle on Rat Island. Brodifacoum Conservation 25W is only manufactured by Bell Laboratories and the bait used was sampled and tested prior to broadcast on the island. Brodifacoum cannot be confused with difenacoum during the anticoagulant screening conducted at DCPAH (Dr. Rhombia, pers. comm.). However, brodifacoum in the bait applied on Rat Island in 2008 is likely the source of difenacoum as a result of molecular debromination of brodifacoum (A. Lehner, DCPAH, pers. comm.).

Bromadiolone was detected in only 1 sample from Rat Island, but indicates how widespread some rodenticides can be in birds that migrate to remote islands even in the Aleutians.

Presence of domoic acid and saxitoxin in significant levels would indicate exposure to these marine toxins which are produced in algal blooms and might help explain the large number of birds found on Rat Island. However, none of the samples tested indicated this was a contributing factor.

Some strains of avian virus and Newcastle disease can infect large numbers of birds and lead to high mortality in a relatively short time. Based on screening results, an outbreak of these diseases did not cause the bird mortality found on Rat Island.

CONCLUSION

Aerial broadcast can provide rapid bait application to large inaccessible areas where it is economically more practical than applying bait from the ground for large-scale eradication of invasive rats on islands. Aerial broadcast of brodifacoum bait risks toxic exposure to

nontarget birds through primary and secondary pathways, and avian mortality was far greater than predicted after the Rat Island bait application. Necropsy results and brodifacoum residue levels observed in carcasses collected on Rat Island in 2009 indicate brodifacoum exposure as the cause of death for most specimens examined. Brodifacoum exposure was widespread across species and trophic levels and affected large numbers of individuals. Brodifacoum persisted in the island environment for at least 9 months, if not longer, and was detected in samples from seabirds, raptors, passerines, shorebirds and marine waterfowl. The documented mortalities and postulated pathways of exposure underestimate nontarget impacts because of delayed carcass search efforts and minimal environmental sampling. At this time, impacts of these bird deaths are not known, however none of the birds species collected are rare or threatened and no rare or threatened birds were known to occur on Rat Island at the time of bait application. Long-term positive benefits may result if rats were the primary or sole cause of population declines and the eradication is successful. Feasibility of large-scale rodent eradication requires careful assessment of potential nontarget effects and mitigation.

ACKNOWLEDGEMENTS

The authors thank Vernon Byrd, Steve Delehanty, and Peter Dunlevy for reviewing this manuscript. The U.S. Fish and Wildlife Service provided funding for necropsy and residue testing.

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