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Management and Conservation

Mercury in Waterfowl From a Contaminated River in Virginia

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ABSTRACT Many bodies of water around the world are contaminated with mercury from historic industrial and mining activities or ongoing atmospheric deposition, resulting in numerous fish consumption advisories. However, concerns about mercury have only rarely led to consumption advisories on waterfowl. In contrast with fish, waterfowl frequently disperse long distances to new watersheds, so hunters and wildlife managers do not know whether waterfowl at a pristine site have spent time at a contaminated site elsewhere. We sampled tissue mercury concentrations of mallards (*Anas platyrhynchos*), wood ducks (*Aix sponsa*), and Canada geese (*Branta canadensis*) at a site contaminated with mercury, during the breeding and hunting seasons. We found that many mallards had bioaccumulated mercury to levels that had the potential to produce reproductive effects and exceeded consumption advisories set for fish by regulatory agencies, whereas this was true for only a few wood ducks and Canada geese. We also documented that mercury-exposed waterfowl from this contaminated site were harvested by hunters as far as 1,054 km away. Our results suggest the need for more proactive sampling of waterfowl for mercury, and likely other bioaccumulating contaminants, in order to allow hunters to make more informed choices about consumption of their harvest.

KEY WORDS Canada goose, consumption advisories, contaminants, ecotoxicology, mallard, mercury, Virginia, waterfowl hunting, wood duck.

Concern about mercury contamination of waterfowl is not a recent phenomenon (Fimreite et al. 1971), but the impact of this ubiquitous pollutant on waterfowl hunting has been minor compared to the profound impact it has had on fishing. Whereas thousands of inland lakes and rivers in the United States are subject to fish consumption advisories due to mercury (United States Environmental Protection Agency 2009), only a single recent mercury advisory on waterfowl has been announced, in Great Salt Lake, Utah (The State of Utah 2005). Mercury from aquatic point sources or atmospheric deposition has the potential to biomagnify up food chains and concentrate in the tissues of higher trophic level animals, and thus poses a potential hazard to the health of waterfowl (Scheuhammer 1987) and humans who consume them (Scholl and Ball 2005). Unlike many freshwater gamefish species, waterfowl migrate and have the potential to switch watersheds within and between seasons. This could reduce their lifetime exposure to a contaminated site, but could also allow contaminated waterfowl to be harvested at an uncontaminated site elsewhere. This transitory behavior makes managing communications about contaminant exposure through waterfowl consumption difficult, because posting site-specific advisories will not inform hunters elsewhere.

Mercury exposure was once thought to be limited to fish-eating birds, with attention focused on eagles, osprey, kingfishers, herons, and loons (Evers et al. 2005). Among waterfowl, only fish-eating mergansers have been singled out for concern (Braune and Malone 2006, Kalisinska et al. 2010). However, recent reports of elevated mercury in terrestrial songbirds (Rimmer et al. 2005; Cristol et al. 2008; Jackson et al. 2011*a*, *b*), and high levels of mercury documented in 3 species of non-piscivorous ducks in Utah, have underscored the potential hazards to hunters of consuming

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any species of waterfowl, including dabblers (Vest et al. 2009). Although fish-eating waterfowl species will inevitably reflect the mercury content of their prey, researchers are less clear how often non-fish eating species, which compose most hunted waterfowl, accumulate enough mercury to pose a hazard to their own or hunter health.

We examined mercury levels in 3 of the most commonly hunted waterfowl species (Raftovich et al. 2010), mallard (*Anas platyrhynchos*), wood duck (*Aix sponsa*), and Canada goose (*Branta canadensis*), at a site with well-documented mercury contamination in local terrestrial and aquatic bird populations (Cristol et al. 2008). Our objectives were to determine whether waterfowl tissues at a contaminated site reached mercury concentrations that 1) exceeded known thresholds for potential harm to avian reproductive performance or 2) exceeded thresholds used for fish consumption advisories. Because some of the waterfowl banded for this study were opportunistically recovered, we also asked 3) whether they potentially exported mercury to distant areas where they might be harvested by hunters.

STUDY AREA

In the 1930s and 1940s, an unknown amount of mercury leaked into the South River from an industrial site in Waynesboro, Augusta County, Virginia (Carter 1977). We sampled waterfowl along 38 km of contaminated South River (Fig. 1). For reference sites, we sampled 2 nearby rivers in the same watershed not known to be contaminated with mercury (Middle and North Rivers; approximate centroid of all study sites 38°12′N, 78°53′W; Fig. 1). At the northern edge of the study area, these 3 rivers join to become the South Fork Shenandoah River, which flows into the Potomac River and eventually empties into Chesapeake Bay. The South and South Fork Shenandoah Rivers have been the subject of a fish consumption advisory for decades (Virginia Department of Health 1977), and extensive study of mercury accumulation in wildlife since 2005 (Bergeron et al. 2007, 2010; Cristol et al. 2008; Wada et al. 2010).

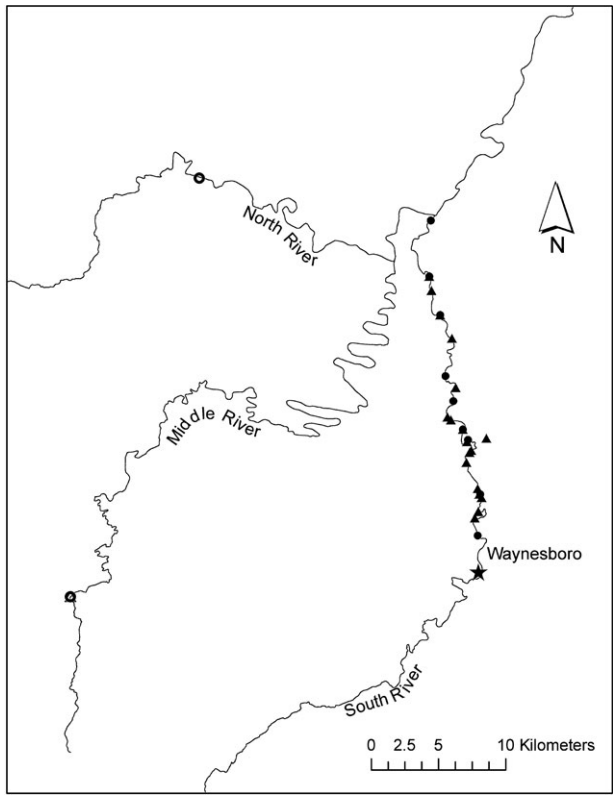

Figure 1. Map of waterfowl sampling sites in Rockingham and Augusta counties, Virginia, USA, 2006–2009. Closed symbols represent samples from mercury-contaminated sites and open symbols indicate reference sites. Triangles represent samples collected during the hunting season, circles represent the breeding season. Star indicates historic source of mercury contamination.

METHODS

Obtaining Samples

We sampled mallard, wood duck, and Canada goose tissue during the spring-summer breeding season and during the fall-winter hunting seasons. During the breeding season, we captured adult waterfowl using decoy traps (Sharp and Lokemoen 1987) baited with a live domestic mallard, spring-loaded nets baited lightly with corn, or wire walk-in nest traps. Upon capture, we non-lethally sampled 3 ml of blood with a 25-gauge syringe and clipped 1 secondary wing feather before affixing a United States Geological Survey (USGS) numbered leg band and releasing at site of capture. We attached radio-transmitters (Pietz et al. 1995, see supplementary material available online at www.onlinelibrary.wiley.com) to mallards ($n = 17$ females) to assist with finding nests and we opportunistically searched for nests of Canada goose and mallard on the shore of the South River. We did not search for wood duck nests because of logistical constraints. When we found a mallard or Canada goose nest, we collected the entire clutch of eggs. We placed all egg and feather samples in doubled zipping plastic bags and stored blood in sealed plastic centrifuge tubes. We kept all samples on ice for 1–6 hours before weighing (eggs only) and freezing them at −25° C until analysis. During the non-breeding (hereafter hunting) season, we obtained breast muscle and wing feathers from all 3 species immediately after they had been harvested by cooperating, licensed hunters on the contaminated portion of the South River during the legal hunting season. We obtained information on incidental detection of birds banded by us during the breeding season, but later harvested by hunters, from the USGS as part of their normal notification process.

Dates of breeding season blood and feather sampling were 7 April–9 July 2006, 5 April–9 May 2007, and 27 March–14 May 2008. We sampled Canada goose eggs from 9 to 22 April 2006, and mallard eggs from 9 April to 7 May 2007 and 2 April to 26 June 2008. One cooperating group of licensed hunters provided muscle and feather samples of mallard ($n = 5$), wood duck ($n = 3$), and Canada goose ($n = 3$) in December 2006 and November 2007–January 2008. Another group of licensed hunters provided the same 3 species (11 mallards, 8 wood ducks, and 10 Canada geese) from September–December 2008 and in October 2009. We collected reference waterfowl only during the 2006 and 2007

breeding seasons, as comparison to reference areas was not the focus of this study.

Because we received band numbers, but not muscle tissue, for incidentally collected waterfowl harvested by hunters, we were unable to directly measure the mercury levels in these ducks at the time of harvest. No published data are available to provide an accurate prediction of the relationship between concentrations of mercury in blood during the breeding season and in muscle during the subsequent hunting season. However, using data from 2 mallards that we banded and sampled for blood during the breeding season and later sampled for muscle tissue at the contaminated site during hunting season, we can estimate the likely muscle mercury level in a hypothetical mallard with a known blood concentration that dispersed from the contaminated area at the end of the breeding season and was harvested at another location during the next hunting season. The 2 mallards for which we have cross-seasonal data had breeding season blood mercury concentrations of 0.375 ppm and 1.055 ppm, and hunting season muscle concentrations of 0.412 ppm and 0.861 ppm, respectively. Thus, the cross-seasonal blood:muscle ratios of the 2 mallards were 0.9:1.0 ppm and 1.2:1.0 ppm. In the absence of any comparable cross-seasonal data in the literature, we used the midpoint of this range (1.0×) for predicting the mercury concentration of the edible portion during the hunting season based on the blood mercury concentration measured during the breeding season.

Mercury Analysis

We analyzed all blood samples without drying, directly from the thawed collection containers. Prior to analysis, we washed all feathers in distilled water and stored them in a low-humidity chamber for 48 hours. We individually freeze-dried all egg samples for 24–48 hours using a Labconco Benchtop Freeze Dry System (Labconco, Inc., Kansas City, MO). Following freeze-drying, we re-weighed each egg to estimate percent moisture for calculating the wet weight mercury concentration. Prior to mercury analysis, we homogenized eggs to a powder using a clean glass stirring rod. We analyzed eggs individually for mercury, but combined values for all eggs in a clutch for 1 mean to avoid pseudoreplication. We presented all tissue concentrations on a wet weight basis.

Determination of total mercury concentration of avian tissues took place at 4 labs: 1) College of William & Mary using a Direct Mercury Analyzer (DMA-80, Milestone, Inc. Shelton, CT); 2) Center for Environmental Sciences and Engineering at the University of Connecticut (using United States Environmental Protection Agency, USEPA, method 245.6 with a Perkin Elmer Flow Injection Mercury System, Milford, CT); 3) Trace Element Research Lab at Texas A&M University (Milestone DMA-80); and 4) Brooks Rand Labs (Seattle, WA using USEPA method 1631 with Cold Vapor Atomic Florescence Spectroscopy). Samples at Brooks Rand Labs were also analyzed for methylmercury using EPA method 1630 modified.

We analyzed avian tissue samples over a 3-year period at 4 labs and obtained quality assurance data (Table 1). In general, before and after every set of 20 samples, we included 2 samples each of 2 standard reference materials (SRM, typically DORM-2 or DORM-3 and DOLT-3 or DOLT-4), 2 methods blanks, and 2 sample blanks. During the period of mercury determination, we spiked samples of blood, egg, or feather expected to have low mercury concentrations with SRM to measure recovery in the appropriate matrix. We included approximately 1 duplicate sample with every 20 samples. Duplicates of blood were not true duplicates because they were collected in 2 tubes from the same individual on the same date and time. Duplicate feather samples were closer to true duplicates because they were created from a larger feather cut into pieces of 1 mm^2 with scissors and homogenized by stirring for 1 minute before measuring duplicate aliquots. We took egg duplicates from large, homogenized, freeze-dried egg samples; they were ideal duplicates. All samples were above minimum detection levels. Quality assurance results were at or exceeded generally accepted standards (Table 1).

We collected all samples under appropriate permits (USGS Bird Banding permit 22636 and Virginia Scientific Collection permits 026945 and 030964). Hunters collected

Table 1. Quality assurance information for total mercury analysis of waterfowl at 4 laboratories: College of William and Mary, Center for Environmental Science and Engineering at University of Connecticut, Trace Elements Research Lab at Texas A&M University, and Brooks Rand Laboratories (mean ± SD (*n*)). We report relative percent difference for duplicate samples, minimum detection limits, percent recoveries for 4 standard reference materials (DORM-2, DORM-3, DOLT-3, and DOLT-4), and percent of added mercury detected in spiked tissue.

	College of William & Mary	University of Connecticut	Texas A&M University	Brooks Rand Laboratories
Duplicates	8.1 ± 10.7 (24)[a]	2.3 ± 7.4 (11)[a,b,c]	11.0 ± 3.3 (8)[b]	0.9 ± 0.6 (7)[d]
Min. detection limit[e]	0.003–0.004	0.002–0.018	0.003–0.007	0.01–0.04
% Recoveries				
DORM-2	101.2 ± 5.0 (47)	101.1 ± 6.4 (7)	97.1 ± 2.4 (9)	
DORM-3				108 ± 11.0 (4)
DOLT-3	100.3 ± 1.6 (22)		104.3 ± 2.6 (9)	
DOLT-4	95.8 ± 2.8 (23)	103 ± 3.2 (7)		108 (1)
Tissue spike	100.0 ± 1.5 (10)	100.1 ± 8.6 (11)	93.0 ± 7.1 (12)	104 ± 10.5 (14)

[a] Egg.
[b] Blood.
[c] Feather.
[d] Muscle.
[e] Parts per million wet weight.

waterfowl within applicable seasons using appropriate licenses.

Data Analysis

We compared all species to published data on mercury in mallards because data are not available for the other species. Breast muscle is the most commonly consumed portion of waterfowl, but no widely accepted standard exists for what level of mercury is safe to consume in waterfowl. Therefore, as an initial effort to determine whether a risk assessment is warranted, we present total mercury concentrations of muscle, collected at the contaminated site during the hunting season or estimated from breeding season blood concentration, in relation to the USEPA mercury screening value for fish tissue (0.3 ppm), as well as the Virginia Department of Health (VDH) guideline of 0.5 ppm and the United States Food and Drug Administration (USFDA) action level of 1.0 ppm. These levels of concern set for fish tissue are based on the number of fish meals over time, as well as other potential sources of mercury, and this may differ from what would be expected for waterfowl hunters. Although it is only a gross screen, using fish consumption advisory guidelines as an estimate for waterfowl consumption seems appropriate because in a study of urban and rural waterfowl hunters, the majority of mercury exposure in the waterfowl hunters' diets came from freshwater fish consumption, suggesting co-occurring exposures to fish and waterfowl (Duchesne et al. 2004).

Statistical Analysis

We performed all statistics in SPSS 19 (SPSS, Inc., Chicago, IL). Mercury measures were log transformed prior to analysis but untransformed data are presented for clarity when indicated. We made comparisons of magnitude using geometric means. We examined differences in mercury levels between species using a 1-way analysis of variance (ANOVA) and used *t*-tests to examine differences between the sexes within species. We back transformed means and 95% confidence intervals from ANOVAs and *t*-tests using the anti-log.

RESULTS

Tissue Mercury Levels

During the breeding season (Mar–Jul), mallard feather mercury on contaminated sites, influenced by each bird's mercury concentration at the time of the previous breeding season's wing molt, was approximately half (53.9%) that of wood ducks, but 3.5× higher than that of Canada geese ($F_{2,\ 114} = 4.53$, $P = 0.013$; Table 2). Mallard blood, influenced by recent dietary intake, had 2.8× higher total mercury concentration than wood ducks and was 8.7× higher than in Canada geese ($F_{2,\ 134} = 19.39$, $P < 0.001$; Table 2). Mercury in mallard clutches, which was deposited by the female prior to laying, was 3.1× higher than in Canada goose clutches ($t_{17} = 3.11$, $P = 0.006$; Table 2); we did not sample wood duck eggs.

Females had higher feather mercury concentrations during the breeding season in both mallards (male mean = 0.90, 95% CI = 0.68–1.21, $n = 73$, female mean = 2.64, 95% CI = 1.49–4.67, $n = 18$, $t_{89} = 3.34$, $P = 0.001$) and wood ducks (male mean = 0.98, 95% CI = 0.40–2.40, $n = 9$, female mean = 3.70, 95% CI = 1.64–8.34, $n = 11$, $t_{18} = 2.31$, $P = 0.03$; Fig. 2). We found no sex difference in blood mercury of mallards, whereas female wood ducks had higher blood mercury concentrations than males (mallard: male mean = 0.57, 95% CI = 0.44–0.73, $n = 75$, female mean = 0.73, 95% CI = 0.46–1.14, $n = 22$, $t_{95} = 0.93$, $P = 0.36$; wood duck: male mean = 0.13, 95% CI = 0.10–0.18, $n = 17$, female mean = 0.37, 95% CI = 0.27–0.50, $n = 17$, $t_{32} = 4.80$, $P < 0.001$). We did not classify Canada geese by sex so no comparison was possible.

During the hunting season (Sep–Jan), mallards harvested at contaminated sites had approximately twice (2.2×) the mercury concentrations in feathers as wood ducks and

Table 2. Total mercury (ppm) in tissues of waterfowl sampled at South River, Virginia in 2006–2009. We present back transformed arithmetic (arith.) and geometric (geo.) means and 95% confidence intervals.

	Breeding season[a]			Hunting season	
	Blood	Feathers	Clutch[b]	Muscle	Feathers
Mallard					
Arith. mean ± SD	0.94 ± 0.87	2.04 ± 2.17	0.60 ± 0.32	0.67 ± 0.66	2.94 ± 2.98
Geo. mean (95% CI)	0.61 (0.49–0.74)	1.10 (0.84–1.44)	0.50 (0.35–0.71)	0.35 (0.18–0.68)	1.53 (0.80–2.92)
Range	0.02–5.41	0.02–12.43	0.16 ± 0.03–1.30 ± 0.09	0.03–2.38	0.28–9.74
n	97	90	15	16	16
Wood duck					
Arith. mean ± SD	0.29 ± 0.19	5.11 ± 6.94		0.09 ± 0.08	1.51 ± 2.24
Geo. mean (95% CI)	0.22 (0.16–0.31)	2.04 (1.14–3.62)		0.05 (0.02–0.11)	0.71 (0.31–1.61)
Range	0.05–0.69	0.31–23.14		0.01–0.262	0.19–7.27
n	34	20		11	10
Canada goose					
Arith. mean ± SD	0.11 ± 0.09	0.59 ± 0.75	0.17 ± 0.06	0.10 ± 0.19	0.68 ± 0.97
Geo. mean (95% CI)	0.07 (0.02–0.18)	0.31 (0.10–0.98)	0.16 (0.08–0.32)	0.03 (0.02–0.08)	0.32 (0.16–0.66)
Range	0.01–0.22	0.08–1.90	0.09 ± 0.01–0.20 ± 0.04	0.01–0.72	0.04–3.60
n	4	5	4	13	13

[a] Arithmetic mean values for mallards breeding on nearby reference rivers: feather 0.225 ± 0.307 ppm, $n = 11$; blood 0.032 ± 0.017 ppm, $n = 13$.
[b] We sampled 15 mallard clutches containing 6–14 eggs (average clutch size 11.1 ± 2.6). We sampled 4 Canada goose clutches containing 3–7 eggs (average 4.5 ± 1.7). Range for clutches indicates arithmetic mean and standard deviation mercury concentration for all eggs in the lowest and highest clutches.

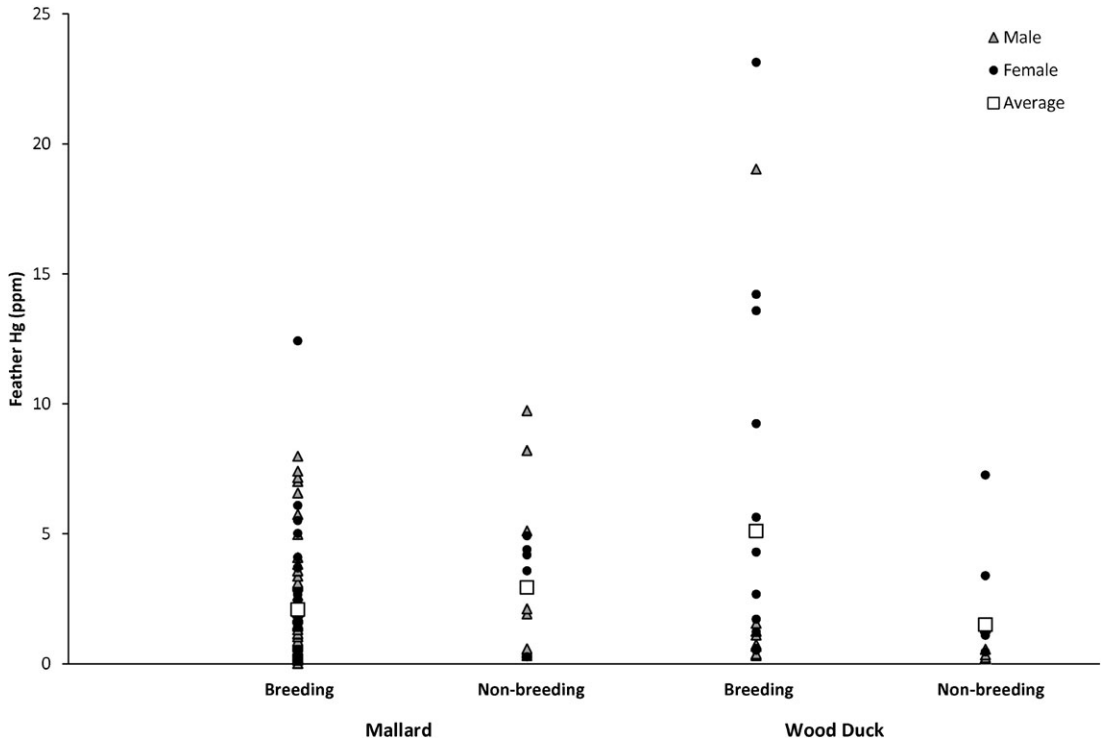

Figure 2. Feather mercury levels (ppm wet weight) of mallard and wood ducks during the breeding and hunting seasons in Virginia, 2006–2009. Squares indicate arithmetic mean, open circles indicate females, and closed triangles are males.

4.8× that of Canada geese ($F_{2,\ 38} = 5.36$, $P = 0.009$; Table 2). Mercury concentrations in pectoral muscles were 7.0× higher in mallards than wood ducks and 11.7× higher in mallards than Canada geese ($F_{2,\ 39} = 12.82$, $P < 0.001$; Table 2).

Mallards collected during the breeding season on 2 reference rivers within the same watershed had uniformly low mercury in feathers (0.15 ppm, 95% CI = 0.08–0.26, $n = 11$) and blood (0.03 ppm, 95% CI = 0.02–0.04, $n = 13$), providing a useful context for interpreting the elevated mercury levels found on the South River.

Effects on Breeding Waterfowl

We report the percentage of the population of each species that exceeded published tissue levels associated with statistically significant negative effects on reproductive success in mallards (Table 3). The arithmetic mean blood mercury level of breeding mallards of both sexes at the South River (0.94 ppm; Table 2) was above the lowest blood level causing reproductive effects in experimentally dosed mallards (0.8 ppm; Heinz 1979); 9 of 22 sampled females (40.9%) exceeding this threshold (Table 3). Of the other 2 species, the mean blood mercury concentrations for both sexes, and the blood mercury concentration of every individual female, were below the level of reproductive effects published for dosed female mallards (Tables 2 and 3).

Arithmetic mean mercury level of mallard clutches (0.60 ppm) was below the lowest reported threshold for various hatching and developmental endpoints (0.74 ppm; Heinz and Hoffman 2003), although 20% of clutches exceeded this threshold. None of the Canada goose clutches exceeded 0.74 ppm.

Table 3. Percent of females or clutches sampled at South River, Virginia in 2006–2008, exceeding minimum concentration in the effects range of mercury tissue levels demonstrated to reduce reproductive success in mallards dosed with dietary mercury.

Species	Tissue	% Exceeding	Effects range[a] (ppm[b])
Mallard	Egg	20.0	0.74–5.9
Mallard	Blood	40.9	0.8–6.0
Wood duck	Blood	0	0.8–6.0
Canada goose	Egg	0	0.74–5.9
Canada goose	Blood	0	0.8–6.0

[a] Egg: Heinz (1979), Heinz and Hoffman (2003), Heinz et al. (2010*a*). Blood: Heinz (1979), Heinz et al. (2010*a*, *b*).
[b] Wet weight concentration in tissue, untransformed data.

Mercury in Edible Portion of Non-Breeding Waterfowl

During the hunting season, 57% of mallards had muscle tissue above the USEPA level of concern for fish consumption, 50% were above the VDH guideline, and 29% exceeded the level set by the USFDA (Table 4). Among 24 wood ducks and Canada geese harvested on the contaminated site, only a single goose exceeded the USEPA and VDH levels and none exceeded USFDA guidelines. We measured total mercury as a proxy for the most bioavailable form, methylmercury, because most mercury in edible waterfowl tissues is in the methylated form. In a subset of our waterfowl samples, we measured methylmercury content at 92 ± 13%, 108 ± 10%, and 87 ± 14% of mercury present in breast muscle of mallard ($n = 11$), wood duck ($n = 8$), and Canada goose ($n = 10$), respectively, or 94 ± 15% overall.

Table 4. Percent of waterfowl samples[a] from South River, Virginia in 2006–2009 exceeding mercury concentrations (wet weight) established as guidelines for fish consumption advisories by the United States Environmental Protection Agency (USEPA), Virginia Department of Health (VDH), or United States Food and Drug Administration (USFDA).

Species	0.3 ppm (USEPA)	0.5 ppm (VDH)	1.0 ppm (USFDA)	Season (*n*)
Mallard	57	50	29	Hunting (14)
Wood duck	0	0	0	Hunting (11)
Canada goose	8	8	0	Hunting (13)
Mallard	75	64	37	Breeding (97)
Wood duck	47	21	0	Breeding (34)
Canada goose	0	0	0	Breeding (4)

[a] Breeding season values estimated from blood mercury concentration; hunting season values analyzed directly from breast muscle tissue.

We did not sample muscle tissue during the breeding season; however, a crude cross-seasonal estimate of mercury concentrations in edible muscle tissue during subsequent hunting season is described above to predict if hunters may be exposed to waterfowl exceeding consumption guidelines set for fish. The muscle mercury concentration estimated from breeding season blood concentration for 75% of mallards was higher than the 0.3 ppm USEPA threshold for concern, whereas approximately half of wood ducks (47%) would likely have exceeded this level (Table 4). Using the intermediate Virginia guidelines, we estimated that 64% of breeding mallards and 21% of wood ducks exceeded recommended levels for fish consumption. Breeding Canada geese fell below all thresholds set for fish consumption.

Incidental Hunter Harvest

Hunters who were not part of this study harvested birds that we had banded on the contaminated sites during the breeding season. We learned of these only if the hunter reported the band to the USGS. Incidental hunter recoveries were: 2 Canada geese (47 km and 417 km from banding site), 6 wood ducks (2 local, 4 ranging from 193 km to 1,054 km from banding site), and 21 mallards (16 local and 5 ranging from 36 km to 575 km from banding site, Figure 3 shows all recoveries >100 km from banding site). Thus, waterfowl banded at the mercury-contaminated South River were harvested by hunters in other watersheds and states (5 mallards and 4 wood ducks, or 3.5% and 11.8% of ducks banded at the contaminated site during the breeding season, respectively).

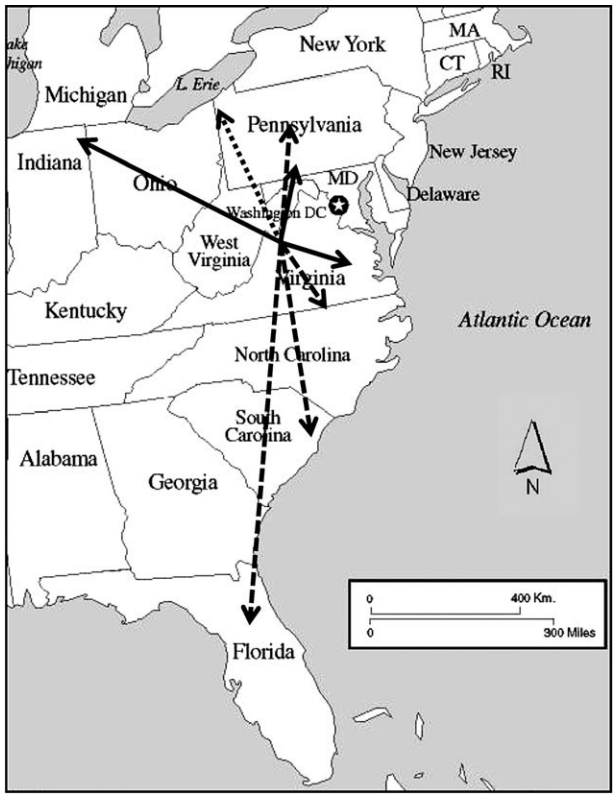

Figure 3. Locations of incidental band recoveries of waterfowl banded at the mercury-contaminated South River in Virginia by hunters >100 km from the banding site (solid = mallard, dashed = wood duck, dotted = Canada goose).

DISCUSSION

Mercury concentrations in blood and feathers of breeding mallards at a mercury-contaminated site in Virginia were more than an order of magnitude higher than levels found in mallards at nearby reference sites. Mallards sampled at reference sites in the same watershed were below or comparable to concentrations reported for dabbling waterfowl from uncontaminated sites in North America (e.g., Hall et al. 2009) and elsewhere (e.g., Bacher and Norman 1984). This suggests that the elevated mercury in waterfowl tissues at the contaminated site originated locally and was not due to atmospheric deposition or other background sources. Breeding wood ducks had less mercury than mallards in blood, as predicted from the relatively greater proportion of vegetation in wood duck diets. However, wood ducks had higher mercury levels in feathers than mallards, which was an unexpected result (discussed below). During the hunting season, mallards had higher muscle and feather mercury levels than the other species. Canada geese had uniformly lower mercury levels than the 2 duck species during the breeding and hunting seasons, as expected from their largely herbivorous diet.

Mallards

In general, wildlife higher on the food web, or with greater annual duration at a contaminated site, would be expected to have the highest tissue mercury concentrations (Hall et al. 2009, Vest et al. 2009). Mallards, being more omnivorous than Canada geese and more likely to be year-round residents at this site than wood ducks, predictably had the highest blood mercury concentrations of the 3 species (Drilling et al. 2002). Because females deposit mercury into eggs in direct proportion to levels in blood (Heinz et al. 2010*b*), we were not surprised that mallard eggs had more mercury than those of Canada geese. Based on published estimates of minimum effects levels, the blood levels of some (40.9%) female mallards suggests the potential for reduced reproductive success, although only a few mallard clutches (20%) exceeded published effects levels. The lack of sex difference in blood levels

of male and female mallards during the breeding season suggests that mercury intake during and after laying is high enough to offset the mercury that females deposit in eggs, consistent with what was found for tree swallows (*Tachycineta bicolor*) at the same site (Brasso et al. 2010).

Wood Ducks

Wood ducks breeding at this site had similar mercury levels in muscle tissue during the hunting season to that reported for spring and summer samples of this species at another mercury-contaminated site in Virginia, the Holston River (0.08 $\pm$ 0.02 ppm; Lindsay and Dimmick 1983). However, breeding season samples on the South River were considerably higher. At the Holston River, none of 5 adults sampled were over the most conservative guideline for human consumption of fish (USEPA: 0.3 ppm), whereas at the South River about half of the wood ducks would have exceeded this level based on a 1:1 conversion from breeding season blood mercury level. The decline from breeding season to hunting season is most likely the result of an influx of autumn migrants from less contaminated sites farther north.

None of the wood ducks sampled at our site during the breeding season exceeded minimum reproductive effects levels based on dietary dosing of female mallards. However, feather levels of wood ducks sampled during the breeding season were unexpectedly high, exceeding that of mallards. This difference was driven by just 5 individual wood ducks, 4 of which were females (Fig. 2). Because feathers contain only mercury present in the body before the previous molt, the 5 birds with unexpectedly elevated mercury in feathers presumably grew the sampled secondary wing feather at the contaminated site the previous year, either as adults or juveniles. This result, although requiring further investigation, suggests that a portion of the females in this wood duck population has high dietary mercury intake for part of the year, perhaps due to a dietary shift from vegetation to animal proteins during egg laying or molt.

Canada Geese

Canada geese, which are primarily herbivorous grazers, had uniformly low mercury concentrations in blood, feather, and egg during the breeding season and feather and muscle during the hunting season. These geese are primarily year-round residents, and, with the exception of 1 bird, tissue levels were well below those proposed to be harmful to birds or humans. Our study suggests that there is little reason to be concerned about the effect of mercury on the health of Canada geese or goose hunters at this site.

MANAGEMENT IMPLICATIONS

We have documented for the first time that waterfowl banded at a mercury-contaminated site are being harvested by hunters in distant watersheds. Hunters unaware of the locally posted mercury advisory for fish consumption on the South River would have no expectation that they had harvested a bird contaminated with mercury. Because we know that at this contaminated site, mallards had an arithmetic mean breeding season blood total mercury concentration of 0.94 ppm, and the half-life of mercury in mallard tissues is months rather than days or weeks (Stickel et al. 1977), their edible muscle concentration when harvested during the next hunting season would likely have been above levels triggering fish consumption advisories (0.3–1.0 ppm). Informing hunters of the possibility of harvesting waterfowl from distant contaminated sites presents a challenge that has not been addressed previously by wildlife or public health officials. This study, as well as the recent closure of hunting seasons for some migratory duck species at Great Salt Lake, Utah, indicates a need for more discussion of proactive sampling, risk assessment, and communication about waterfowl consumption advisories for mercury in waterfowl.

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