Bird Conservation International (2010) 20:112–123. © BirdLife International, 2009
doi:10.1017/S095927090999030X

Threats of environmental mercury to birds: knowledge gaps and priorities for future research

CHAD L. SEEWAGEN

Summary

Anthropogenic emissions of mercury have doubled over the past two centuries. Mercury is a dangerous neurotoxin that threatens human health and fish and wildlife populations. The effects of mercury on birds have been relatively well-studied in the laboratory and in nature. Several aspects of neurology, physiology, behaviour, and reproduction have been shown to be adversely affected. Many studies have documented ataxia, lethargy, reduced appetite, reduced egg production, poor hatching success, and aberrant parental care in birds exposed to mercury.

The majority of the research done to date, however, has been focused on select taxa (waterbirds), trophic levels (piscivores), habitat types (aquatic systems), geographic regions (North America and Europe), and life history stages (reproduction), leaving the assessment of mercury's threats to birds incomplete. Successful bird conservation strategies are dependent on a comprehensive understanding of the threats facing populations. Here, I discuss the significant knowledge gaps that remain and subsequently suggest priorities for future mercury research in birds. Studies of mercury in terrestrial, insectivorous, and/or passerine species, and how mercury affects migration are especially recommended to fill gaps in our present understanding.

Introduction

Mercury is a powerful neurotoxin that poses significant health risks to humans and wildlife (D'Itri and D'Itri 1978, Wolfe *et al.* 1998). Anthropogenic inputs of mercury into air, water, and soil have resulted in a two- to threefold increase in global deposition over the past 200 years (Driscoll *et al.* 2007), with heavily populated urban and industrial areas often exhibiting the most elevated environmental mercury levels (Landis *et al.* 2002, Dennis *et al.* 2005). However, mercury's persistence in the atmosphere and ability to travel great distances from points of origin has allowed it to become a truly global pollutant, even contaminating areas without local sources (e.g. Antarctica; Wilson *et al.* 2006).

Primary sources of anthropogenic mercury emissions include coal and oil combustion, lead, zinc, steel, and cement production, gold mining, and waste incineration and disposal (Driscoll *et al.* 2007, Pacyna *et al.* 2006). Total mercury emissions, and the contribution of each source, differ greatly among countries and continents and between the northern and southern hemispheres. Over the past decade, multiple international conventions have been formed to identify and implement strategies for effective reductions in mercury emissions. Most of this activity has occurred in developed countries in Europe and North America. As a result, recent emissions trends show a general reduction in these areas, whereas emissions continue to rise in most developing countries (Pacyna *et al.* 2006).

At the regional scale, local patterns of mercury deposition across the landscape can vary widely. Areas where humans, fish, and wildlife are at increased risk of mercury exposure are not necessarily areas of high mercury deposition (Evers *et al.* 2007). Several landscape characteristics influence the degree of mercury accumulation, conversion to methylmercury, and exposure to biota in an area (Driscoll *et al.* 2007). This spatial heterogeneity at small scales complicates identification of areas where mercury may be particularly harmful; hence, widespread monitoring networks are needed. When hotspots and the most direct sources of contamination are successfully identified, large reductions in local emissions can have quick and significant effects at this scale (Davis *et al.* 2007, Driscoll *et al.* 2007, Evers *et al.* 2007).

Birds are considered excellent bio-indicators of environmental mercury contamination (Evers *et al.* 2005) and sometimes serve in part as the basis for drafting mercury regulation policies or provide measures of success following policy implementation (e.g. NYSDEC 2006, Driscoll *et al.* 2007). As such, mercury levels in birds have been widely recorded around the world (Gochfeld 1980, Burger *et al.* 1992, 1993, 1997; Burger and Gochfeld 1991, 1993; Janssens *et al.* 2001). However, relatively few studies have investigated the actual consequences of observed mercury levels on free-living birds' condition, fitness, or survival. Fewer still have examined species outside North America and Europe. Beyond their limited geographical diversity, studies of mercury in birds have been disproportionately focused on particular taxa, foraging guilds and trophic levels, ecosystems, and life-history stages. Consequently, our understanding of the threats of mercury to birds remains incomplete. Here, I briefly summarize the documented effects of mercury on birds, identify information gaps, and subsequently suggest priority topics for future investigation. Readers are directed elsewhere for comprehensive reviews of the known effects of mercury on birds (Eisler 1987, Thompson 1996, Wolfe *et al.* 1998, Scheuhammer *et al.* 2007), as the focus of this commentary is on the relationships between mercury and avian biology that remain poorly understood.

Adverse effects of mercury in birds

Mercury is most available and harmful to birds and other biota in the form of methylmercury (Thompson and Furness 1989, Driscoll *et al.* 2007). Inorganic mercury is most readily converted to methylmercury under anaerobic conditions in marine or freshwater systems such as wetlands, lakes, and reservoirs, although recent evidence suggests significant methylation may also occur in terrestrial systems (Rimmer *et al.* 2005, Driscoll *et al.* 2007). Methylmercury bioaccumulates up food chains, reaching the most toxic levels in animals at upper trophic positions. It follows that predatory species associated with aquatic habitats are at the greatest risk of methylmercury accumulation (Evers *et al.* 2005).

Most investigations into the effects of mercury on birds have examined aspects of reproduction. Earlier studies commonly compared some measure of reproductive success across populations of birds with different average mercury concentrations and implied a causal relationship without necessarily accounting for potential confounding factors (e.g. Fimreite 1974). Some studies have compared mercury levels observed in wild birds to levels shown to cause adverse effects in laboratory animals (e.g. Burger and Gochfeld 1997). Perhaps the most thorough studies of mercury on bird reproduction are those that investigate mercury levels and multiple reproduction parameters within individual animals (e.g. Evers *et al.* 2003, 2008). Mercury's effects on birds are far-ranging and its impacts on reproduction are usually the endpoint of more direct effects on behaviour, neurology, and physiology.

Behaviour

Field and laboratory studies have found high mercury burdens in birds to result in lethargy, loss of appetite, and reduced motivation to forage. Bouten *et al.* (1999) noted that dosing captive Great Egrets *Ardea alba* with methylmercury altered activity budgets, with dosed birds spending more time sitting and less time engaged in activities such as preening than control birds. Dosed

https://doi.org/10.1017/S095927090999030X Published online by Cambridge University Press

birds additionally had reduced appetites and showed less motivation to hunt fish. Spalding *et al.* (2000a) and Sepulveda *et al.* (1999) found a similar relationship between mercury and appetite in captive and wild Great Egrets, respectively. In Common Loons *Gavia immer*, Evers *et al.* (2008) documented a significant inverse relationship between methylmercury burden and time spent engaged in high-energy activities such as foraging for chicks and themselves, locomotion, and agonistic interactions with others. They also documented aberrant incubation behaviour by parents. Insufficient time spent incubating and foraging for chicks were suspected to be among the significant causes of the reduced reproductive success observed in loons with relatively high mercury levels. Nocera and Taylor (1998) found loon chicks with the highest mercury levels to ride on the backs of their parents least often, and therefore expend more energy and expose themselves to predation more than is typical.

Neurology

Mercury is a neurotoxin that affects coordination in humans and many other animals (D'Itri and D'Itri 1978, Wolfe *et al.* 1998). Ataxia is a common behavioural characteristic of birds suffering from relatively high mercury burdens (Finley *et al.* 1979, Laties and Evans 1980, Bouten *et al.* 1999). Spalding *et al.* (2000b) found captive Great Egrets dosed with methylmercury to suffer severe lesions to nervous system tissues, resulting in slower reaction times to various stimuli and difficulty flying, perching, and standing. Heinz and Hoffman (1998) similarly found captive Mallards *Anas platyrhynchos* dosed with methylmercury to have difficulty standing, although dosing levels exceeded those typically observed in nature.

Laties and Evans (1980) showed methylmercury to affect the operant discrimination ability of birds, when the success rates of Wood Pigeons *Columbia livia* trained to complete a task significantly declined after methylmercury dosing.

Physiology

Mercury has been associated with reductions in egg production, egg size, hatching success, and fertility in several field and laboratory studies (Fimreite 1974, Finley and Stendell 1978, Heinz and Hoffman 1998, Evers *et al.* 2003; but see Thompson *et al.* 1991). Each is expected to ultimately result in reduced reproduction rates within wild populations.

Methylmercury may reduce the production of haem, a component of haemoglobin that binds to and transports oxygen in blood (Olsen *et al.* 2000). Consequently, birds with high methylmercury levels may have reduced oxygen carrying capacity and poor ability to sustain high-intensity exercise such as long-distance flight. Olsen *et al.* (2000) found Common Loons with relatively high methylmercury levels had shorter underwater dive durations during foraging and attributed this reduced ability to hold breath to low haem production.

Energy for feather growth is provided by protein in muscle tissue where much of ingested methylmercury is deposited. Additionally, methylmercury has a high affinity for keratin and thus a large proportion of ingested mercury travels to growing feathers (Fournier *et al.* 2002). It is not surprising that methylmercury may therefore affect feather development or function in some capacity. Evers *et al.* (2008) documented increased flight feather asymmetry in loons with higher methylmercury burdens and suggested this may significantly impact individual fitness by decreasing flight efficiency.

Reproduction

Many of the effects of mercury on birds' behaviour, neurology, and physiology indirectly influence reproductive success. Reduced egg production, egg size, and hatching success will reduce fecundity in wild birds (Meyer *et al.* 1998, Burgess and Meyer 2008, Evers *et al.* 2008). Aberrant parenting behaviour, such as that observed in Common Loons (Evers *et al.* 2008), will likely lead to low chick survival. Aberrant behaviour of chicks may further contribute to reduced survival (Nocera and Taylor 1998), although in most cases it appears methylmercury has little direct effect on chicks due to their ability to sequester it in newly grown feathers and away from living tissue (Fournier *et al.* 2002, Merrill *et al.* 2005, Longcore *et al.* 2007).

Survival

Determining the effect of mercury on adult bird survival is complicated by contributions from countless other variables that can simultaneously influence survival rates of wild animals and confound analyses. Additionally, the large, long-term datasets required for powerful survival estimates are seldom available. It is likely that for these reasons, there have been few attempts to measure the effects of mercury on survival in wild birds.

Thompson *et al.* (1991) reported no effect of mercury concentration on the return of Great Skuas *Catharacta skua* to their breeding colony the following year. Meyer *et al.* (1998) similarly noted the likelihood of Common Loons returning to their breeding grounds between years was unaffected by their total mercury levels, suggesting mercury may not reduce adult survival. However, loons are long-lived birds and long-term effects of mercury exposure may not manifest in reduced survival until later in life. Mitro *et al.* (2008) used 10 years of Common Loon mark-recapture/re-sight data from North America to model survival rates and investigate a potential effect of mercury. The study found no significant effect on survival; although, despite the large dataset, statistical power was only sufficient for detecting differences in survival $> 3\%$ between high and low total mercury level groups. The authors nonetheless argue that even 3% reductions in survival could cause significant population declines in long-lived species such as loons.

Knowledge gaps and priorities for future research

The majority of mercury research done to date has been focused on select taxonomic groups, foraging guilds and trophic levels, ecosystems, countries and regions, and life history stages. As such, large knowledge gaps remain and further assessment of mercury's risks to birds is needed (Table 1).

Taxonomy

Nearly all mercury research on birds (field and laboratory) has examined species that inhabit aquatic systems, as they are always expected to be at greatest risk for methylmercury exposure and accumulation. These primarily include species of loons (Gaviiformes), wading birds (Ciconiiformes), seabirds (Charadriiformes), and waterfowl (Anseriformes). Although these groups are widely considered to be the most vulnerable to environmental mercury, they are not necessarily the only groups of birds being impacted. Full risk assessments will require consideration of birds beyond those traditionally associated with mercury contamination (Burger *et al.* 1997).

Songbirds (Passeriformes) comprise the largest Order of birds, with approximately 5,400 species representing over half of all described bird species (Gill 1995). Many of these species are experiencing steep population declines and are of conservation concern (Robins *et al.* 1989, Askins *et al.* 1990, Sanderson *et al.* 2006, Butcher and Niven 2007). Yet, until recently the threat of mercury to songbirds has been largely overlooked because of their low trophic positions and usual association with terrestrial habitats (Burger *et al.* 1997, 2004).

Reports of detectable mercury and methylmercury concentrations in wild songbirds are increasing (Janssens *et al.* 2001, Adair *et al.* 2003, Evers *et al.* 2005, Rimmer *et al.* 2005, Shriver *et al.* 2006, Brasso and Cristol 2008, Cristol *et al.* 2008), but it is uncertain whether the levels

Table 1. Relatively well- and under-studied areas concerning the effects of mercury on birds.

	Taxonomic group	Geographic region	Diet/ trophic level	Habitat association	Life history
Well-studied	Gaviiformes, Charadriiformes, Ciconiiformes, Anseriformes, Falconiformes	North America, Europe	Piscivores, carnivores	Lakes, rivers, wetlands, oceans	Reproduction
Under-studied	Passeriformes	Tropical regions, S. America, Africa	Insectivores fruigivores, granivores	Temperate forests, tropical rainforests, other terrestrial systems	Migration (flight and stopover periods), total annual survival

observed are great enough to be detrimental to songbird health or fitness. Brasso and Cristol (2008) found female Tree Swallows *Tachycineta bicolor* with high total mercury burdens produced fewer fledglings than individuals with lower total mercury levels. Similarly, Longcore *et al.* (2007) found total mercury concentrations were higher in some unhatched than hatched Tree Swallow eggs. In contrast, several studies have found total mercury levels in free-living songbirds to be lower than levels shown to cause adverse effects in published laboratory or field studies of non-passerine species (Custer *et al.* 2001, 2006; Adair *et al.* 2003, Hothem *et al.* 2008), suggesting the songbirds examined were not accumulating harmful levels of mercury. However, the validity of this approach is questionable because threshold effect levels may in fact be lower in passerines than other Orders that are commonly used by such studies for reference (Longcore *et al.* 2007, Tsipoura *et al.* 2008, Heinz *et al.* 2009). For example, Tsipoura *et al.* (2008) noted total mercury levels of unhatched Marsh Wren *Cistothorus palustris* eggs were significantly greater than those of successfully hatched eggs even though the unhatched eggs' mercury levels were below those reported to be toxic to various non-passerine species.

Despite the growing interest in mercury accumulation in passerines, it remains poorly understood what concentrations are necessary to cause the sub-lethal negative effects that have been well-documented in other Orders (lethal toxicity levels in some passerines are reported by Finley *et al.* 1979). Captive dosing studies of passerines similar to those conducted on aquatic birds (e.g. Spalding *et al.* 2000a,b) are needed to establish lowest observable adverse effect levels and would improve interpretation of past and future measurements of mercury in free-living songbirds. Additional field studies that examine mercury and multiple health or fitness parameters within individual songbirds (e.g. Brasso and Cristol 2008) should also be a priority (Rimmer *et al.* 2005).

Foraging guild and trophic level

Mercury bioaccumulates up food chains as methylmercury and reaches the highest concentrations in predatory species. For this reason mercury has been commonly studied in piscivores, and to a lesser-extent, carnivores such as hawks, falcons, and owls (Thompson 1996), while other guilds have been comparatively ignored. Although species at lower trophic positions are expected to have lower levels of total mercury and methylmercury, these levels may still be great enough to cause adverse effects. This may be particularly true for insectivores that are not as high on food chains as piscivores or carnivores, but may nevertheless occupy trophic positions where methylmercury can sufficiently bioaccumulate. This is evident in some of the studies of insectivorous passerines referenced above. For example, Evers *et al.* (2005) found blood mercury levels of insectivorous Red-winged Blackbirds *Agelaius phoeniceus* exceeded those of various piscivorous bird species. Yet, additional research remains needed to conclusively determine if the total mercury or methylmercury levels observed in insectivorous birds are great enough to cause adverse effects. Captive dosing studies would help elucidate the consequences of the mercury and methylmercury levels that have been documented in wild insectivores. Further mercury monitoring in wild insectivores is also needed, as at present, very few species and geographic locations have been examined. Primarily frugivorous and granivorous species do not appear to be at risk of significant mercury/methylmercury accumulation (Burger *et al.* 1997, Rimmer *et al.* 2005, Fredricks *et al.* 2009), but studies of such species are few.

Ecosystems

Aquatic systems are most efficient at converting inorganic mercury into methylmercury, thereby placing aquatic species at increased risk of methylmercury exposure (Evers and Clair 2005, Evers *et al.* 2005, 2007, Driscoll *et al.* 2007). Among aquatic systems, methylmercury availability is believed to increase from marine to riverine to lake and wetland systems (Evers *et al.* 2005). Total mercury and methylmercury concentrations in bird species that inhabit each of these systems have been widely documented (Muirhead and Furness 1988, Thompson *et al.* 1992, Burger and Gochfeld 1993, Thompson 1996, Evers *et al.* 2005, 2007, 2008). In contrast, terrestrial habitats and their wildlife have received little attention concerning mercury (Lacher and Goldstein 1997, Rimmer *et al.* 2005, Driscoll *et al.* 2007).

The mechanisms for methylation of inorganic mercury in terrestrial systems, such as temperate forests, are poorly understood. It is unclear whether the majority of methylmercury present in forest foliage is directly deposited from the atmosphere, or originates as dry-deposition inorganic mercury and is then methylated within leaves (Rimmer *et al.* 2005, Driscoll *et al.* 2007). Few studies have examined the accumulation of methylmercury by strictly terrestrial birds whose diet is not closely linked to aquatic habitats. Rimmer *et al.* (2005) found detectable methylmercury levels in five species of insectivorous passerines nesting in high elevation montane forests of northeastern USA and southeastern Canada. In a Virginia, USA watershed, Cristol *et al.* (2008) found forest birds with diets of terrestrial origin had significantly greater total mercury concentrations than aquatic-feeding birds; however, the study sites were in a historically contaminated industrial area. These studies demonstrate that temperate forests can potentially expose birds to significant amounts of mercury and methylmercury, but additional support would be beneficial.

Tropical forests are well-known for their high biodiversity and conservation priority. Thorough studies of mercury in these systems are lacking (Lacher and Goldstein 1997). Methylation processes are unclear, but some characteristics of tropical forests suggest methylation efficiency and methylmercury exposure to wildlife may be great. The long, wide, and complex food webs that are typical of tropical systems may provide great biomagnification potential, and the drastic variations in soil moisture are expected to enhance methylation processes (Burger 1996).

Burger *et al.* (1993) did not find detectable concentrations of mercury among various passerine species in the rainforests of Papua New Guinea. In contrast, Rimmer *et al.* (2005) found total mercury burdens of Bicknell's Thrushes *Catharus bicknelli* during winter on tropical Hispaniola to be significantly greater than during their breeding season in the temperate northeastern USA and southeastern Canada - the regions of greatest mercury deposition in North America.

As in temperate areas, mercury contamination and biotic uptake in tropical systems likely varies dramatically at regional and local scales. Widespread documentation and monitoring of mercury accumulation in tropical areas is sorely needed (Burger 1996, Lacher and Goldstein 1997). Lacher and Goldstein (1997) declared mercury research in the tropics among the highest priorities in ecotoxicology. Sources of anthropogenic mercury emissions in temperate and tropical countries differ greatly, with fossil fuel combustion often accounting for most emissions in the former and gold mining accounting for most emissions in the latter (Pfeiffer *et al.* 1993, Lacher and Goldstein 1997, Porcella *et al.* 1997, Pacyna *et al.* 2006). This limits the application of our knowledge of mercury transport and fate, and strategies for effective emissions controls in temperate systems to that in tropical systems.

Geography

Mercury appears to have been studied in birds in North America and Europe more than any other continents. Within North America, the northeastern USA and southeastern Canada have been examined most extensively (see Evers and Clair 2005, Evers *et al.* 2005, Driscoll *et al.* 2007). Elsewhere in the world, mercury levels in birds have been measured in a wide variety of areas (e.g. Gochfeld 1980, Burger *et al.* 1992, 1993; Burger and Gochfeld 1991, 1993), but reports are sporadic. Comprehensive mercury monitoring is lacking outside North America and Europe, especially in many developing countries where emission trends are rising (Burger 1996, Lacher and Goldstein 1997, Pacyna *et al.* 2006). China alone accounts for 28% of annual global mercury emissions, mainly due to its reliance on coal to meet increasing energy demands (Pacyna *et al.* 2006). Impacts on Asian birds and other biota should be closely monitored.

Life history

Prior studies of mercury's effects on birds have been limited to general aspects of health, survival, and reproduction. Mercury's effects on other life history stages, such as migration, remain largely unknown and should be a priority for future research. Migration is the most challenging period in a migratory bird's life cycle and has been estimated to account for as much as 85% of total annual adult mortality (Sillett and Holmes 2002). Further, migration performance may have carry-over effects into subsequent seasons (Newton 2006). Events occurring during migration can thus directly and indirectly influence bird population levels.

Migration for many species consists of alternating bouts of long-distance flying and rapid refuelling during stopovers (Moore *et al.* 1995). The adverse neurological, physiological, and behavioural effects of mercury that have been documented in non-migrating birds provide ample evidence to suspect that high mercury burdens would hinder migrants during both of these activities. Flight feather asymmetry (Evers *et al.* 2008) and reduced oxidative carrying capacity of blood (Olsen *et al.* 2000) caused by mercury could conceivably weaken flight efficiency, whereas lethargy, ataxia, and reduced appetite/motivation to forage (Nocera and Taylor 1998, Bouten *et al.* 1999, Sepulveda *et al.* 1999, Spalding *et al.* 2000a) may affect stopover refuelling ability. It is also plausible that *en route* migrants experience surges in circulating methylmercury levels as a result of protein catabolism during long-distance flights. Methylmercury bound in muscle and other lean tissues may be re-mobilized into the bloodstream when protein is broken down to provide flight energy, water, or citric acid cycle intermediaries (Jenni and Jenni-Eiermann 1998), consequently delivering additional methylmercury to the brain and other nervous system components. How mercury affects bird migration remains unstudied and warrants greater attention.

The categories above are of course not mutually exclusive and broad overlap occurs. For example, terrestrial, insectivorous, migratory, passerines fall into most of these categories. The research needs identified are also not exhaustive. Not included above is the need for laboratory studies of birds that more closely mimic mercury concentrations observed in nature. Laboratory studies should also more frequently measure and report mercury levels in the same tissues that are typically sampled in field studies, such as blood and feathers. Laboratory studies often only report mercury levels in organs measured after study subjects die or are euthanased which complicates interpretation of wild bird mercury levels that are measured non-invasively (Burger and Gochfeld 1997). The interaction of mercury with other contaminants in birds also needs to be further examined. Selenium, for example, may ameliorate some of mercury's effects (Thompson 1996, Heinz and Hoffman 1998) while worsening others (Heinz and Hoffman 1998), but the relationship between the two is not entirely clear (see also Cuvin-Aralar and Furness 1991, Khan and Wang 2009).

Conclusion

Dramatic increases in world-wide mercury emissions have occurred over the past two centuries as a product of human population growth and industry. Environmental mercury contamination threatens human and wildlife populations. Reducing emissions is therefore a global concern, yet trends continue to rise in many parts of the world.

Birds are clearly vulnerable to mercury contamination. Much is known about mercury's effects on birds, but many relationships between mercury and bird biology remain poorly understood. The taxonomic groups, geographic ranges, life history stages, habitat associations, and foraging guilds of birds that are significantly threatened by mercury pollution need to be better identified. Successful bird conservation strategies are dependent on a comprehensive understanding of the threats facing populations. Additional research into how mercury is impacting birds will likely benefit conservation efforts.

Acknowledgements

This manuscript was improved by comments on earlier versions by H. A. L. Henry and S. B. Elbin. I am grateful to D. C. Evers for sparking my interest in the effects of mercury on birds. Support during preparation of the manuscript was provided by the University of Western Ontario and the Wildlife Conservation Society.

References

Adair, B. M., Reynolds, K. D., McMurry, S. T. and Cobb, G. P. (2003) Mercury occurrence in prothonotary warblers inhabiting a national priorities list site and reference areas in southern Alabama. *Arch. Environ. Contam. Toxicol.* 44: 265–271.

Askins, R. A., Lynch, J. F. and Greenburg, R. (1990) Population declines in migratory birds in eastern North America. *Current Ornithol.* 7: 1–57.

Bouten, S. N., Frederick, P. C., Spalding, M. and McGill, H. (1999) Effects of chronic, low concentrations of dietary methylmercury on the behavior of juvenile great egrets. *Environ. Toxicol.* 18: 1934–1939.

Brasso, R. L. and Cristol, D. A. (2008) Effects of mercury exposure on the reproductive success of tree swallows (*Tachycineta bicolor*). *Ecotoxicology* 17: 133–141.

Burger, J. (1996) Ecological effects and biomonitoring for mercury in tropical ecosystems. *Water Air Soil Pollut.* 97: 265–272.

Burger, J. and Gochfeld, M. (1991) Lead, mercury, and cadmium in feathers of tropical terns in Puerto Rico and Australia. *Arch. Environ. Contam. Toxicol.* 21: 311–315.

Burger, J. and Gochfeld, M. (1993) Heavy metal and selenium levels in feathers of young egrets and herons from Hong Kong and Szechuan, China. *Arch. Environ. Contam. Toxicol.* 25: 322–327.

Burger, J. and Gochfeld, M. (1997) Risk, mercury levels, and birds: relating adverse laboratory effects to field biomonitoring. *Environ. Res.* 75: 160–172.

Burger, J., Parsons, K., Benson, T., Shukla, T., Rothstein, D. and Gochfeld, M. (1992) Heavy metal and selenium levels in young cattle egrets from nesting colonies in the northeastern United States, Puerto Rico, and Egypt. *Arch. Environ. Contam. Toxicol.* 23: 435–439.

Burger, J., Laska, M. and Gochfeld, M. (1993) Metal concentrations in feathers of birds from Papua New Guinea forests: evidence of pollution. *Environ.Toxicol. Chem.* 12: 1291–1296.

Burger, J., Kennamer, R. A., Lehr Brisbin, I. and Gochfeld, M. R. (1997) Metal levels in mourning doves from South Carolina: potential hazards to doves and hunters. *Environ. Res.* 75: 173–186.

Burger, J., Bowman, R., Wolfenden, G. E. and Gochfeld, M. (2004) Metal and metalloid concentrations in the eggs of threatened Florida scrub jays in suburban habitat from south-central Florida. *Sci. Tot. Environ.* 328: 185–193.

Burgess, N. M. and Meyer, M. W. (2008) Methylmercury exposure associated with reduced productivity in common loons. *Ecotoxicology* 17: 83–91.

Butcher, G. S. and Niven, D. K. (2007) *Combining data from the Christmas bird count and the breeding bird survey to determine the continental status and trends of North American birds.* New York, USA: National Audubon Society.

Cristol, D. A., Brasso, R. L., Condon, A. M., Fovargue, R. E., Friedman, S. L., Hallinger, K. K., Monroe, A. P. and White, A. E. (2008) The movement of aquatic mercury through terrestrial food webs. *Science* 320: 335.

Custer, T. W., Custer, C. M., Dickerson, K., Allen, K., Melancon, M. J. and Schmidt, L. J. (2001) Polycyclic aromatic hydrocarbons, aliphatic hydrocarbons, trace elements, and monooxygenase activity in birds nesting on the North Platte River, Casper, Wyoming, USA. *Environ. Toxicol. Chem.* 20: 624–631.

Custer, T. W., Custer, C. M., Goatcher, B. L., Melancon, M. J., Matson, C. W. and Bickham, J. W. (2006) Contaminant exposure of barn swallows nesting on Bayou D'Inde, Calcasieu Estuary, Louisiana, USA. *Environ. Monitor. Assess.* 121: 541–558.

Cuvin-Aralar, L. A. and Furness, R. W. (1991) Mercury and selenium interaction: a review. *Ecotoxicol. Environ. Safety* 21: 348–364.

Davis, D. D., McClenahen, J. R. and Hutnik, R. J. (2007) Use of the moss *Dicranum montanum* to evaluate recent temporal trends of mercury accumulation in oak forests of Pennsylvania. *Northeast Nat.* 14: 27–34.

Dennis, I. F., Clair, T. A., Driscoll, C. T., Kammen, N., Chalmers, A., Shanley, J., Norton, S. A. and Kahl, S. (2005) Distribution patterns of mercury in lakes and rivers of Northeastern North America. *Ecotoxicology* 14: 113–123.

D'Itri, P. A. and D'Itri, F. M. (1978) Mercury contamination: a human tragedy. *Environ. Manage.* 2: 3–16.

Driscoll, C. T., Han, Y., Chen, C. Y., Evers, D. C., Fallon Lambert, K., Holsen, T. M., Kamman, N. C. and Munson, R. K. (2007) Mercury contamination in forest and freshwater ecosystems in the Northeastern United States. *BioScience* 57: 17–28.

Eisler, R. (1987) *Mercury hazards to fish, wildlife, and invertebrates: a synoptic review.* Laurel, MD: U.S. Fish and Wildlife Service, Patuxent Wildlife Research Centre. U.S. Fish and Wildlife Service Biological Report 85.

Evers, D. C. and Clair, T. A. (2005) Mercury in northeastern North America: a synthesis of existing databases. *Ecotoxicology* 14: 7–14.

Evers, D. C., Taylor, K. M., Major, A., Taylor, R. J., Poppenga, R. H. and Scheuhammer, A. M. (2003) Common loon eggs as indicators of methylmercury availability in North America. *Ecotoxicology* 12: 69–81.

Evers, D. C., Burgess, N. M., Champoux, L., Hoskins, B., Major, A., Goodale, W. M., Taylor, R. J., Poppenga, R. and Daigle, T. (2005) Patterns and interpretation of mercury exposure in freshwater avian communities in Northeastern North America. *Ecotoxicology* 14: 193–221.

Evers, D. C., Han, Y., Driscoll, C. T., Kamman, N., Goodale, M., Lambert, K., Holsen, T., Chen, C., Clair, T. and Butler, T. (2007) Biological mercury hotspots in the northeastern United States and southeastern Canada. *BioScience* 57: 29–43.

Evers, D. C., Savoy, L. J., DeSorbo, C. R., Yates, D. E., Hanson, W., Taylor, K. M., Siegel, L. S., Cooley, Jr., J. H., Bank, M. S., Major, A., Munney, K., Mower, B. F., Vogel, H. S., Schoch, N., Pokras, M., Goodale, M. W. and Fair, J. (2008) Adverse effects from environmental mercury loads on breeding common loons. *Ecotoxicology* 17: 69–81.

Fimreite, N. (1974) Mercury contamination of aquatic birds in northwestern Ontario. *J. Wildl. Manage.* 38: 120–131.

Finley, M. T. and Stendell, R. C. (1978) Survival and reproductive success of black ducks fed methylmercury. *Environ. Pollut.* 16: 51–64.

Finley, M. T., Stickel, W. H. and Christensen, R. E. (1979) Mercury residues in tissues of dead and surviving birds fed methylmercury. *Bull. Environ. Contam. Toxicol.* 21: 105–110.

Fredricks, T. B., Fedynich, A. M., Benn, S. and Ford, L. (2009) Environmental contaminants in white-winged doves (*Zenaida asiatica asiatica*) from the Lower Rio Grande Valley of Texas, USA. *Arch. Environ. Contam. Toxicol.* 57: 387–396.

Fournier, F., Karasov, W. H., Kenow, K. P., Meyer, M. W. and Hines, R. K. (2002). The oral bioavailability and toxicokinetics of methylmercury in common loon (*Gavia immer*) chicks. *Comp. Biochem. Physiol. A* 133: 703–714.

Gill, F. B. (1995) *Ornithology*. Second editon. New York, USA: W.H. Freeman and Company.

Gochfeld, M. (1980) Mercury levels in some seabirds of the Humboldt Current, Peru. *Environ. Pollut.* 22: 197–205.

Heinz, G. H. and Hoffman, D. J. (1998) Methylmercury chloride and selenomethionine interactions on health and reproduction in mallards. *Environ. Toxicol. Chem.* 17: 161–166.

Heinz, G. H., Hoffman, D. J., Klimstra, J. D., Stebbins, K. R., Kondrad, S. L. and Erwin, C. A. (2009) Species differences in the sensitivity in avian embryos to methylmercury. *Arch. Environ. Contam. Toxicol.* 56: 129–138.

Hothem, R. L., Trejo, B. S., Bauer, M. L. and Crayon, J. J. (2008) Cliff swallows *Petrochelidon yrrhonota* as bioindicators of environmental mercury, Cache Creek Watershed, California. *Arch. Environ. Contam. Toxicol.* 55: 111–121.

Janssens, E., Dauwe, T., Bervoets, L. and Eens, M. (2001) Heavy metals and selenium in feathers of great tits (*Parus major*) along a pollution gradient. *Environ. Toxicol. Chem.* 20: 2815–2820.

Jenni, L. and Jenni-Eiermann, S. (1998) Fuel supply and metabolic constraints in migrating birds. *J. Avian Biol.* 29: 521–528.

Khan, M. A. K. and Wang, F. (2009) Mercury-selenium compounds and their toxicological significance: Toward a molecular understanding of the mercury-selenium antagonism. *Environ. Toxicol. Chem.* 28: 1567–1577.

Lacher, T. E. and Goldstein, M. I. (1997) Tropical ecotoxicology: status and needs. *Environ. Toxicol. Chem.* 16: 100–111.

Landis, M. S., Vette, A. F. and Keeler, G. J. (2002) Atmospheric mercury in the Lake Michigan basin: influence of the Chicago/Gary urban area. *Environ. Sci. Technol.* 36: 4508–4517.

Laties, V. G. and Evans, H. L. (1980) Methylmercury-induced changes in operant discrimination by the pigeon. *J. Pharmacol. Exp. Therapeutics* 214: 620–628.

Longcore, J. R., Haines, T. A. and Halteman, W. A. (2007) Mercury in tree swallow food, eggs, bodies, and feathers at Acadia National Park, Maine, and an EPA Superfund site, Ayer, Massachusetts. *Environ. Monitor. Assess.* 126: 129–143.

Merrill, E. H., Hartigan, J. J. and Meyer, M. W. (2005) Does prey biomass or mercury exposure affect loon chick survival in Wisconsin? *J. Wildl. Manage.* 69: 57–67.

Meyer, M. W., Evers, D. C., Hartigan, J. J. and Rasmussen, P. S. (1998). Patterns of common loon (*Gavia immer*) mercury exposure, reproduction, and survival in Wisconsin, USA. *Environ. Toxicol. Chem.* 17: 184–190.

Mitro, M. G., Evers, D. C., Meyer, M. W. and Piper, W. H. (2008) Common loon survival rates and mercury in New England and Wisconsin. *J. Wildl. Manage.* 72: 665–673.

Moore, F. R., Gauthreaux, S. A., Kerlinger, P. and Simons, T. R. (1995) Habitat requirements during migration: important link in conservation. Pp. 121–144 in T. E. Martin and D. M. Finch, eds. *Ecology and management of Neotropical migratory birds: a synthesis and review of critical issues*. New York: Oxford University Press.

Muirhead, S. J. and Furness, R. W. (1988) Heavy metal concentrations in the tissues of seabirds from Gough Island, South Atlantic Ocean. *Mar. Pollut. Bull.* 19: 278–283.

New York State Department of Environmental Conservation. (2006) Mercury Work Group recommendations to meet the mercury challenge. http://www.dec.ny.gov/docs/permits_ej_operations_pdf/meetmercurychallenge.pdf. on 1/4/2008.
Newton, I. (2006) Can conditions experienced during migration limit the population levels of birds? *J. Ornithol.* 147: 146–166.
Nocera, J. J. and Taylor, P. D. (1998) In situ behavioral response of common loons associated with elevated mercury exposure. *Conserv. Ecol.* 2:10.
Olsen, B., Evers, D. C. and DeSorbo, C. (2000) Effect of methylated mercury on the diving frequency of the common loon. *J. Ecol. Res.* 2: 67–72.
Pacyna, E. G., Pacyna, J. M., Steenhuisen, F. and Wilson, S. (2006) Global anthropogenic mercury emission inventory for 2000. *Atmos. Environ.* 40: 4048–4063.
Pfeiffer, W. C., Lacerda, L. D., Salomons, W. and Malm, O. (1993) Environmental fate of mercury from gold mining in the Brazilian Amazon. *Environ. Rev.* 1: 26–37.
Porcella, D. B., Ramel, C. and Jernelov, A. (1997) Global mercury pollution and the role of gold mining: An overview. *Water Air Soil Pollut.* 97: 205–207.
Rimmer, C. C., McFarland, K. P., Evers, D. C., Miller, E. K., Aubry, Y., Busby, D. and Taylor, R. J. (2005) Mercury levels in Bicknell's thrush and other insectivorous passerine birds in montane forests of the northeastern United States and Canada. *Ecotoxicology* 14: 223–240.
Robins, C. S., Sauer, J. R., Greenberg, R. S. and Droege, S. (1989) Population declines in North American birds that migrate to the Neotropics. *Proc. Nat. Acad. Sci.* 86: 7658–7662.
Sanderson, F. J., Donald, P. F., Pain, D. J., Burfield, I. J. and van Bommel, F. P. J. (2006) Long-term population declines in Afro-Palearctic migrant birds. *Biol. Conserv.* 131: 93–105.
Scheuhammer, A. M., Meyer, M. W., Sandheinrich, M. B. and Murray, M. W. (2007) Effects of environmental methylmercury on the health of wild birds, mammals, and fish. *Ambio* 36: 12–18.
Sepulveda, M. S., Williams, G. E., Frederick, P. C. and Spalding, M. G. (1999) Effects of mercury on health and first-year survival of free-ranging great egrets from southern Florida. *Arch. Environ. Contam. Toxicol.* 37: 369–376.
Shriver, W. G., Evers, D. C., Hodgman, T. P., MacCulloch, B. J. and Taylor, R. J. (2006) Mercury in sharp-tailed sparrows breeding in coastal wetlands. *Environ. Bioindicators* 1: 129–135.
Sillett, T. S. and Holmes, R. T. (2002) Variation in survivorship of a migratory songbird throughout its annual cycle. *J. Anim. Ecol.* 71: 296–308.
Spalding, M. G., Frederick, P. C., McGill, H. C., Bouton, S. N. and McDowell, L. R. (2000a) Methylmercury accumulation in tissues and its effects on growth and appetite in captive great egrets. *J. Wildl. Dis.* 36: 411–422.
Spalding, M. G., Frederick, P. C., McGill, H. C., Bouton, S. N., Richey, L. J., Schumacher, I. M., Blackmore, C. G. and Harrison, J. (2000b) Histologic, neurologic, and immunologic effects of methylmercury in captive great egrets. *J. Wildl. Dis.* 36: 423–435.
Thompson, D. R. 1996. Mercury in birds and terrestrial mammals. Pp. 341–356 in W. N. Beyer, G. H. Heinz and A. W. Redmond-Norwood, eds. *Environmental contaminants in wildlife: interpreting tissue concentrations*. South Carolina, USA: Lewis Publisher.
Thompson, D. R. and Furness, R. W. (1989) The chemical form of mercury stored in South Atlantic seabirds. *Environ. Pollut.* 60: 305–317.
Thompson, D. R., Hamer, K. C. and Furness, R. W. (1991) Mercury accumulation in great skuas *Catharacta skua* of known age and sex, and its effects upon breeding and survival. *J. Appl. Ecol.* 28: 672–684.
Thompson, D. R., Furness, R. W. and Walsh, P. M. (1992) Historical changes in mercury concentrations in the marine ecosystem of the North and North-East Atlantic Ocean as indicated by seabird feathers. *J. Appl. Ecol.* 29: 79–84.
Tsipoura, N., Burger, J., Feltes, R., Yacabucci, J., Mizrahi, D., Jeitner, C. and Gochfeld, M. (2008) Metal concentrations in three species

of passerine birds breeding in the Hackensack Meadowlands of New Jersey. *Environ. Res.*107: 218–228.

Wilson, S. J., Steenhuisen, F., Pacyna, J. and Pacyna, E. G. (2006) Mapping the spatial distribution of global anthropogenic mercury atmospheric emission inventories. *Atmos. Environ*. 40: 4621–4632.

Wolfe, M. F., Schwarzbach, S. S. and Sulaiman, R. A. (1998) Effects of mercury on wildlife: a comprehensive review. *Environ. Toxicol. Chem*. 17: 146–160.

CHAD L. SEEWAGEN

Department of Ornithology, Wildlife Conservation Society, 2300 Southern Boulevard, Bronx, NY, 10460, USA and Department of Biology, University of Western Ontario, 1151 Richmond Street North, London, ON N6A 3K7, Canada. Email: cseewagen@wcs.org

Received 22 January 2009; revision accepted 12 May 2009;
Published online 11 December 2009