Marine birds and trace elements in the temperate North Pacific

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Abstract

This review focuses on cadmium, lead, mercury, and selenium because they have been found in tissues of marine birds at concentrations that cause adverse effects in other species. Exposure of birds to trace elements can be measured by analyzing their food, water, air, or bodily tissues. The preferred tissue for analysis varies according to the trace elements of interest. The liver is useful for measuring most elements (including cadmium, lead, mercury, and selenium) when recent exposure of the bird is being assessed. Cadmium, mercury, and selenium should be measured in both the liver and the kidneys, because the ratio of concentrations between these two tissues helps assess environmental exposure. Cumulative lead exposure may be assessed by analyzing bones. Elemental concentrations in feathers may be good indicators of exposure to certain elements, if they are considered carefully. Concentrations in bird eggs reflect exposure of the female to mercury and selenium, but eggs are not considered useful in assessing exposure of birds to cadmium or lead.

Bird tissues and eggs from several areas in the North Pacific have been analyzed for trace elements. However, effects of environmental contaminants on marine birds of the temperate North Pacific have not been studied comprehensively. Based on studies in the North Pacific and in the field and laboratory elsewhere, acute effects of trace elements probably are not likely to occur in marine birds (ingestion of paint chips by albatross fledglings on Midway Atoll is an exception), but chronic toxicity of trace elements does occur. The greatest needs for information include (1) histopathological and other indicators of tissue damage resulting from environmental contaminants, (2) reproductive success, notably egg hatchability and cause-specific nest failure, (3) possible interactions among trace elements, such as mercury–selenium and cadmium–zinc, that may affect their absorption and toxicity, and (4) geographic patterns of trace elements in birds of the North Pacific and temporal trends in concentrations of these chemicals in bird tissues. Interrelationships between mercury and selenium in marine birds are of interest because concentration ratios are highly variable and not consistent with findings in marine mammals.

Résumé

L'étude insiste sur le cadmium, le plomb, le mercure et le sélénium, des substances relevées dans les tissus des oiseaux marins, en des concentrations qui causent des dommages chez d'autres espèces. On mesure l'exposition des oiseaux aux éléments traces par l'analyse de leur nourriture, de leurs excrétions urinaires, de l'air dans leur organisme ou de leurs tissus corporels. Les tissus privilégiés aux fins de l'analyse dépendent des éléments à mesurer. Le foie convient pour mesurer la plupart des éléments (le cadmium, le plomb, le mercure et le sélénium), lorsque le scientifique veut évaluer l'exposition récente de l'oiseau. Pour le cadmium, le mercure et le sélénium, il faut en mesurer la présence dans le foie et dans les reins, puisque le rapport de concentration entre les deux tissus facilite l'évaluation de l'exposition ambiante. L'analyse des os permet d'évaluer l'exposition cumulative au plomb. Soumises à un examen minutieux, les concentrations dans le plumage peuvent être de bons indicateurs de l'exposition à certains éléments. Les concentrations dans les oeufs sont des indicateurs de l'exposition de la femelle au mercure et au sélénium, ce qui n'est pas le cas pour le plomb et le cadmium.

On a examiné les tissus et les oeufs d'oiseaux marins dans plusieurs régions du Pacifique Nord, pour en mesurer les concentrations d'éléments traces, sans pour autant étudier exhaustivement les effets des contaminants de l'environnement sur les oiseaux marins des zones tempérées du Pacifique Nord. Selon les résultats des études réalisées dans le Pacifique Nord, dans d'autres régions et en laboratoire, les éléments traces ne semblent pas causer d'effets aigus chez les oiseaux marins (sauf dans les cas d'ingestion d'éclats de peinture par les petits d'albatros dans l'atoll Midway). On relève, cependant, des cas de toxicité chronique. Il importe de recueillir davantage d'information 1) sur les indicateurs histopathologiques et les autres indicateurs des dommages tissulaires dus aux contaminants du milieu; 2) sur la réussite de la reproduction (notamment, l'éclosion des oeufs) et l'échec de la nidification attribuable à des causes précises; 3) sur les interactions possibles entre les éléments traces (mercure-sélénium et cadmium-zinc, par exemple), qui peuvent influer sur l'absorption et la toxicité; et 4) sur la distribution géographique des éléments traces relevés dans les oiseaux du Pacifique Nord et les tendances temporelles des concentrations tissulaires. Les rapports entre le mercure et le sélénium, qui contaminent les oiseaux marins, présentent un intérêt particulier, parce que les coefficients de concentration sont très variables et différents des résultats obtenus chez les mammifères marins.

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1. Introduction

Ohlendorf et al. (1978) summarized the published information concerning exposure and biological effects of contaminants in marine birds up to 1975. The present paper focuses primarily on more recent publications, particularly those concerning the temperate North Pacific. However, information is included for marine birds in other regions and from experimental studies with various avian species insofar as they help put the North Pacific information into context or interpret its possible significance.

This review focuses on cadmium, lead, mercury, and selenium because these elements are found in tissues of marine birds at concentrations that cause adverse effects in other species. Because interactions among various trace elements (e.g., mercury–selenium, cadmium–zinc, and others) can affect their absorption and toxicity, concentrations of other elements in bird tissues should also be measured to make an accurate toxicological assessment (Scheuhammer 1987).

The exposure and effects of contaminants in Canadian seabirds also have been summarized recently (Noble and Elliott 1986; Elliott et al. 1989; Noble 1990), and two other papers in this symposium summarize recent information concerning organochlorines (Elliott and Noble) and oil (Burger and Fry) as contaminants. In addition, several general reviews may be of interest, including the Contaminant Hazard Review series by Eisler (1985–1989) and papers by Scheuhammer (1987), Ohlendorf and Fleming (1988), Tanabe (1988), and Ohlendorf (1989).

2. Exposure and effects of trace elements

Several elements (arsenic, chromium, cobalt, copper, fluorine, iodine, iron, manganese, molybdenum, nickel, selenium, silicon, tin, vanadium, and zinc) are essential in small amounts for animal nutrition because they are an integral part of at least one enzyme (Underwood 1977; Clarkson 1979; Robbins 1983). Animals have a variety of homeostatic mechanisms with regard to these essential trace elements, so they are less likely to produce toxic effects than are the non-essential elements. Nevertheless, those control mechanisms can be overwhelmed or circumvented and some essential elements, such as selenium, can produce toxic effects in wild birds (Ohlendorf et al. 1988, 1989; Ohlendorf 1989).

Non-essential trace elements also can occur in animal tissues, and the variable concentrations of selected trace elements have been used to determine exposure of the animals to these environmental contaminants (Underwood 1977; Scheuhammer 1987). Among the non-essential elements are aluminum, cadmium, lead, mercury, silver, and others. Skewed (log-normal) distribution patterns often have been reported for the concentrations of these elements in organs, whereas the essential elements usually have a normal distribution.

2.1. Exposure of marine birds to trace elements

2.1.1. *Selection of sample tissues*

Exposure of birds to trace elements can be measured by analyzing their food, water, air, or selected bodily tissues. Other reviews (e.g., Eisler 1985–1989) report contaminant concentrations in various environmental media (e.g., water, plants, and animals); the focus here is on trace element concentrations in tissues and eggs of birds.

In some studies (e.g., Osborn et al. 1979; Hamanaka 1984; Ohlendorf et al. 1985; Honda et al. 1986) trace element concentrations are reported for several tissues to show distribution within the body, but concentrations usually are reported only for one or two tissues. The preferred tissue for analysis varies according to the trace elements of interest. Thus tissues should be selected on the basis of trace element distribution within the body and other factors, such as comparability with other studies and objectives of the study.

Analysis of the liver is appropriate for assessing recent exposure of birds to most elements (including cadmium, lead, mercury, and selenium). For monitoring populations with low exposure to cadmium: when cadmium-induced renal toxicity is unlikely, the kidneys rather than the liver are better for measuring cadmium. Under those circumstances cadmium concentrations in the liver may be low enough to present analytical difficulties (Scheuhammer 1987). Cadmium, mercury (Scheuhammer 1987), and selenium (Ohlendorf 1989; Ohlendorf et al. 1990) should be measured in both the liver and the kidneys, because the ratio of concentrations between these two tissues helps assess environmental exposure. Differences in liver:kidney ratios for these elements indicate differences between acute and chronic exposure, chemical forms of the elements in the diet, and relative exposure in comparison to normal background levels.

Lead exposure also may be measured by analyzing kidneys or bones (Scheuhammer 1987). Among the soft tissues, kidneys usually contain highest lead concentrations and are considered a good indicator of recent exposure, whereas lead concentrations in bones are considered the best index of lifelong exposure. In addition, δ-aminolevulinic acid dehydratase (ALAD) activity in whole blood can be assayed easily to test for possible lead-induced inhibition of this enzyme (as a measure of recent exposure), and blood can be analyzed also for lead to assess the bird's exposure to this metal (Scheuhammer 1987).

Elemental concentrations in feathers may be good indicators of avian exposure to certain elements, if they are considered carefully. It is important to recognize that elements in feathers may have been excreted by the bird at the time the feathers were growing (which may have been months earlier and thousands of miles away from the collection site), or they may have adhered to the feathers through external contamination (Goede and de Bruin 1984, 1985, 1986, Furness et al. 1986; Braune and Gaskin 1987a, 1987b; Scheuhammer 1987). Concentrations also may have been reduced through leaching. Different kinds of feathers from the same bird may contain different concentrations of trace elements, depending partly on when the feathers were grown during the moult cycle. Seasonal changes in trace element concentrations may occur in the liver and other avian tissues because of feather moult and other factors (Osborn 1979) and should be considered when studies are being planned.

Mercury and selenium concentrations in bird eggs reflect exposure of the female to those elements (Ohlendorf et al. 1978; Scheuhammer 1987; Ohlendorf 1989). However, eggs are not considered useful for assessing exposure of birds to cadmium or lead (Pattee 1984; Scheuhammer 1987; Leonzio and Massi 1989). Because very little cadmium is transferred to eggs regardless of dietary levels the birds consumed, reports of high cadmium concentrations in eggs should be considered cautiously. Although some lead is transferred to eggs (primarily to the eggshells), concentrations are typically low and variable, and they do not correlate well with dietary exposure.

Table 1
Concentrations (μg/g dry weight) of cadmium, lead, mercury, and selenium in bird tissues considered to represent normal background and toxic levels[a]

Element	Background				Toxic				References[b]
	Liver	Kidney	Bone	Egg	Liver	Kidney	Bone	Egg	
Cadmium	<3	<2–8	?	<0.5	?	>100–200	?	?	1, 2, 3
Lead	<0.5–5	<1–10	2–5	<0.5	>5	>15	>10	?	2, 4
Mercury	<1–10	<1–10	?	<1	>6	>6–12(?)	?	>1.5–4.5	2, 3, 5
Selenium	3–10	5–12	?	1–3	>10–30	>10–30	?	>8	3, 6, 7, 8, 9, 10

[a] Most of these values are for birds in general: normal and toxic (associated with impaired health or reproduction) values for marine birds may be somewhat different, but insufficient data were available to adequately compare marine birds with other avian species. Question marks indicate that values could not be determined.
[b] 1 = Eisler 1985a, 2 = Scheuhammer 1987, 3 = Ohlendorf and Harrison 1986, 4 = Eisler 1988b, 5 = Eisler 1987, 6 = Eisler 1985b, 7 = Ohlendorf 1989, 8 = Ohlendorf and Skorupa 1989, 9 = Skorupa et al. 1990, 10 = Skorupa and Ohlendorf 1991.

Trace element concentrations in bird feces may be a good indicator of exposure to certain elements, particularly to inorganic forms that are not readily absorbed by the birds (Scheuhammer 1987; Leonzio and Massi 1989). Leonzio and Massi (1989) suggested that analysis of feces would be a useful method of determining avian exposure to metals, particularly for colonial species from which feces could be collected fairly easily. However, biologically incorporated elements, such as methylmercury and organic selenium, in the diet seem to be particularly important biologically because they are readily absorbed and often more toxic than inorganic forms (see Scheuhammer 1987; Ohlendorf 1989). Thus analysis of feces may not adequately reflect the hazard of those elements because they could be present at low concentrations in feces despite their occurrence at elevated levels in food items or tissues of the birds.

2.1.2. *Concentrations in tissues*

Trace element concentrations in tissues are reported on a dry-weight basis (unless stated otherwise) to avoid errors associated with varying amounts of moisture (Adrian and Stevens 1979). Concentrations that were originally reported on a wet-weight basis were sometimes converted to a dry-weight basis by assuming a moisture content of 70% for liver and 75% for kidney, which are typical values for samples analyzed through our research centre. Concentrations in eggs are typically reported on a fresh-weight basis, which is the wet-weight concentration corrected for moisture loss that occurred during incubation (Stickel et al. 1973). However, when trace elements are being reported in a wide variety of media having very different moisture contents, it may be appropriate to report all concentrations, including those in eggs (which average about 70% moisture), on a dry-weight basis. Regardless of whether concentrations are reported on a dry-weight or wet-weight basis, moisture content of samples should be included to facilitate conversion.

Table 1 presents a summary of cadmium, lead, mercury, and selenium concentrations in selected tissues that are considered to represent normal background concentrations and those that have been associated with impaired health or reproduction of birds. These concentrations are presented as reference points for the following discussion about trace element concentrations in North Pacific seabirds.

Bird tissues and eggs from several areas in the North Pacific have been analyzed for trace elements. In 1983, some of the Laysan Albatross *Diomedea immutabilis* fledglings at Midway Atoll, Hawaii, died of lead poisoning (Sileo and Fefer 1987). Lead concentrations in the livers of affected birds were 6–110 μg/g, compared to 1.2–6.0 μg/g in normal albatross fledglings. Weathered paint chips from buildings on the islands were the apparent source of lead. Aside from unusual situations such as that on Midway, the greatest risks of significant exposure of birds to hazardous levels of lead are to migratory waterfowl that frequent hunted areas and ingest spent lead shot; avian predators that eat game shot by hunters; and birds that forage extensively near heavily travelled roads, mining facilities, smelters, refineries, or metal-finishing industries (Eisler 1988b).

Low concentrations of cadmium, lead, and mercury (means <1 μg/g) were reported in feathers of Laysan Ducks *Anas laysanensis*, which are nearly flightless and endemic to Laysan Island, Hawaii (Stoneburner and Harrison 1981a). In contrast, exceptionally high concentrations of cadmium (75 μg/g wet weight, or about 250 μg/g dry weight) and selenium (66 μg/g; about 220 μg/g dry weight) were reported in the eggs of Sooty Terns *Sterna fuscata* from Lisianski Island, Hawaii (Stoneburner and Harrison 1981b). However, those values for cadmium and selenium are questionable because (1) very little cadmium is transferred from the female to her eggs (Scheuhammer 1987), (2) cadmium was below 1 μg/g and selenium averaged <5 μg/g in eggs of Sooty Terns, Wedge-tailed Shearwaters *Puffinus pacificus*, and Red-footed Boobies *Sula sula* from four colonies throughout the Hawaiian Islands (Ohlendorf and Harrison 1986), and (3) concentrations of cadmium and selenium in eggs should not exceed those in livers of the adult birds (Scheuhammer 1987; Ohlendorf 1989; Ohlendorf and Skorupa 1989). Mercury concentrations in the tern eggs from Lisianski (0.15 μg/g wet weight, about 0.5 μg/g dry weight) seem reasonable, but those reported for tern eggs from the Dry Tortugas, Florida (7.9 μg/g, about 26 μg/g dry weight), were several times higher than those in livers of the adult birds incubating them (Stoneburner and Harrison 1981b). Because mercury concentrations are normally higher in the liver than in eggs produced by the bird, the mercury value for eggs from the Dry Tortugas also seems questionable.

Concentrations of four essential elements (copper, iron, manganese, and zinc) and two toxic non-essential metals (cadmium and mercury) were measured in liver, kidney, and muscle tissue of 19 pelagic seabird species (N = 150) collected during 1982–1987 in the North Pacific and neighbouring waters (Honda et al. 1990). Essential metal concentrations were generally highest in the liver and less variable than the toxic metal concentrations among and within each species. Iron concentrations in the muscle were higher in alcids than in the other families. Zinc concentrations varied among species and were correlated with cadmium concentrations. Cadmium and mercury concentrations were highest in the liver or kidney and varied widely among species and by diets. Mercury concentrations were extraordinarily high in Black-footed Albatrosses *Diomedea nigripes*, exceeding 300 μg/g wet weight in two of 12 individuals, and seemed to be due to constraints on the elimination of mercury. Some geographical differences in cadmium and mercury concentrations in the seabirds were observed, but were considered natural rather than due to environmental pollution.

Hamanaka (1984) described cadmium and zinc concentrations measured in livers, kidneys, and muscles from a similar series of seabirds (14 species, N = 149) from the North Pacific and Bering Sea during 1973–1979. Comparative distributions of both elements in various tissues of Thick-billed Murres *Uria lomvia* and Tufted Puffins *Fratercula cirrhata* also were described. Mean cadmium concentrations in kidneys exceeded 40 µg/g in seven species, including the Sooty Shearwater *P. griseus*, Pink-footed Shearwater *P. creatopus*, Laysan Albatross, Northern Fulmar *Fulmarus glacialis*, Tufted Puffin, Thick-billed Murre, and Least Auklet *Aethia pusilla*. Individual birds of three species (Thick-billed Murre, Tufted Puffin, Pink-footed Shearwater) had kidney cadmium concentrations exceeding 120 µg/g, and in two species (Sooty Shearwater, Laysan Albatross) individual values exceeded 200 µg/g. Hamanaka (1984) attributed the higher cadmium concentrations in these species to a higher percentage of squids in their diets and considered the age of the birds to be a possible contributing factor. Because the birds were collected far from industrialized areas, the source of cadmium in the squids (and other prey) is unknown. Cheng et al. (1984) suggested that oceanic insects (*Halobates sericeus*) may be an important source of cadmium in some marine birds of the North Pacific.

Mean concentrations of cadmium, copper, mercury, selenium, silver, and zinc in tissues of Surf Scoters *Melanitta perspicillata* and Greater Scaups *Aythya marila* from San Francisco Bay were greater than those observed in these species from other areas (Ohlendorf and Fleming 1988; White et al. 1989). Mercury and selenium concentrations in these diving ducks were equal to or greater than those associated with impaired health or reproduction of dabbling ducks (*Anas* spp.) studied elsewhere. However, the diving ducks are wintering residents on San Francisco Bay, and reproductive effects have not been assessed in these birds.

Surf Scoters and Greater Scaups from the vicinity of Vancouver, British Columbia, were analyzed by Vermeer and Peakall (1979). Concentrations of lead, mercury, silver, and zinc were higher in ducks from the vicinity of a sewer outfall than in ducks from another site about 22 km away from the outfall. Mean concentrations of copper, lead, mercury, silver, and zinc differed between species, apparently reflecting variation in prey and feeding habitat.

Mercury concentrations (µg/g, wet weight) were measured in a series of eggs and livers of seabirds from the western coast of Canada in 1968–1972 (Noble and Elliott 1986). Mean mercury in eggs ranged from 0.42 µg/g in Pigeon Guillemots *Cepphus columba* to 0.05 µg/g in Cassin's Auklets *Ptychoramphus aleuticus*. Mercury in livers ranged from a mean of 2.21 µg/g in three Marbled Murrelets *Brachyramphus marmoratus* to 0.10 µg/g in a single Glaucous-winged Gull *Larus glaucescens*.

A few birds from Puget Sound, including Pigeon Guillemots, Glaucous-winged Gulls, and Great Blue Herons *Ardea herodias*, were analyzed for several trace elements (Riley et al. 1983). Seven elements (cadmium, cobalt, iron, lead, mercury, selenium, and zinc) occurred at different mean concentrations in livers and kidneys of gulls from different regions of the sound. Mercury concentrations in the livers of two herons from Commencement Bay (12 and 16 µg/g) were higher than in three others from elsewhere in the sound. Selenium levels in the liver (77 µg/g) and kidneys (60 µg/g) of a guillemot from Elliot Bay and another from the Strait of Juan de Fuca (5′ and 60 µg/g) were high by comparison with those in the gu'.s and herons, but comparable data are not available for guille nots from other regions. Otherwise, concentrations of cadmium, lead, mercury, and selenium in these birds from Puget Sound were not remarkable.

Mercury (0.26 and 0.27 µg/g wet weight) and selenium (0.28 and 0.31 µg/g) concentrations in Double-crested Cormorant *Phalacrocorax auritus* eggs from two colonies in the Strait of Juan de Fuca, Washington, were below levels that have been associated with reproductive problems (Henny et al. 1989). Although these cormorants experienced poor reproductive success, the cause seemed unrelated to the measured organochlorines and trace elements.

Livers of Dunlins *Calidris alpina*, Black-bellied Plovers *Pluvialis squatarola*, and Long-billed Dowitchers *Limnodromus scolopaceus* from Washington State and California in 1984–85 were analyzed for mercury and selenium (Custer and Myers 1990). Mercury concentrations were highest in Dunlins from Bodega Bay (19 µg/g) and Salinas River (16 µg/g), California. Median mercury concentration was higher in Dunlins (8.2 µg/g) than in dowitchers (2.7 µg/g) or plovers (1.0 µg/g). Selenium concentrations were highest in plovers from Samish Bay (30 µg/g) and Kennedy Creek (27 µg/g), Washington, but median concentrations were similar among species (Dunlin 13 µg/g, dowitcher 11 µg/g, and plover 9.4 µg/g). Further studies are warranted at sites where mercury and selenium occurred at highest concentrations because sublethal effects on bird health or reproduction could occur there.

Cadmium, lead, and mercury concentrations were measured in tissues (livers, kidneys, muscle, bone, and feathers) of 16 species of aquatic and terrestrial birds from Korea (Lee et al. 1989). Relatively high mean concentrations of cadmium were found in livers (3.3 µg/g wet weight) and kidneys (25 µg/g wet weight) of Black-tailed Gulls *Larus crassirostris*, the representative seabird in this study. Highest cadmium concentrations (37 µg/g wet weight) in kidneys of gulls from Masan Bay near an industrialized region were in the range where kidney lesions have been found in other seabirds (Nicholson and Osborn 1983). However, lead and mercury concentrations were not particularly high in gull tissues.

Trace element concentrations have been reported in seabirds from many areas other than the North Pacific, and many of those publications were included in other recent reviews (see Eisler 1985, 1989; Scheuhammer 1987; Ohlendorf 1989). Additional information is available on trace elements in seabirds from Peru (Gochfeld 1980), eastern and Arctic Canada (Noble and Elliott 1986, Braune 1987; Noble 1990; Elliott et al., in press), northern Europe (Barrett et al. 1985; Frank 1986; Blomqvist et al. 1987; Norheim 1987), southern Europe (Leonzio et al. 1986a, 1986b; Renzoni et al. 1986), the South Atlantic (Muirhead and Furness 1988), and Antarctica (Norheim et al. 1982; Honda et al. 1986; Norheim 1987). Concentrations of some trace elements — particularly cadmium — were higher in seabirds from some of those regions than in birds from the North Pacific.

2.2. Effects of trace elements in marine birds

Few studies have been conducted of biological effects induced by trace elements in birds of the North Pacific, but somewhat more information is available from other areas. Assessments of effects must consider possible interactions among trace elements (and also with other factors) that may alter toxicity of the various elements (Whanger 1985; Scheuhammer 1987; Ohlendorf 1989).

2.2.1. *Toxicology, physiology, and pathology*

Lead poisoning caused epizootic mortality of Laysan Albatross fledglings at Midway Atoll, Hawaii, in 1982 and 1983 (Sileo and Fefer 1987). Sick albatrosses were unable to retract their wings, causing a "droop-wing" appearance. They had elevated concentrations of lead in their blood, livers, and kidneys and acid-fast intranuclear inclusion bodies in their kidneys. Degenerative lesions were present in the myelin of some brachial nerves. (See Eisler 1988b for a description of other signs of lead poisoning in birds.) Weathered paint samples collected from buildings on Midway contained up to 247 500 µg lead/g and 1012 µg mercury/g. Mercury toxicosis and plastic impaction were other possible causes of death in these birds.

My search revealed no other reports of toxic effects induced by trace elements among seabirds in the North Pacific. However, cadmium (Lee et al. 1989), mercury (Ohlendorf and Fleming 1988; Custer and Myers 1990), and selenium (Ohlendorf and Fleming 1988; White et al. 1989) in the tissues of these birds have been measured at concentrations at least as high as those associated with effects on health or reproduction in other species of aquatic birds.

Cadmium (100–200 µg/g) and mercury (5–13 µg/g) concentrations in tissues have been associated with kidney lesions in pelagic seabirds (Nicholson and Osborn 1983; Nicholson et al. 1983). The metal concentrations at which damage began, and at which biochemical changes could be detected, were below those considered as relatively safe for humans by the World Health Organization. However, these lesions may have resulted from natural exposure of the birds to cadmium in their diet.

Sublethal exposure to cadmium may also adversely affect the testes or cause anemia, retarded growth, bone-marrow hyperplasia, and cardiac hypertrophy (Eisler 1985b; Scheuhammer 1987). It is unclear whether these effects result from direct cadmium toxicity or cadmium-induced disturbances of normal metabolism of essential trace elements such as iron and zinc.

In addition to kidney lesions such as those in certain seabirds (see Nicholson and Osborn 1983; Nicholson et al. 1983), mercury causes neurological damage and reduced food intake leading to weight loss, progressive weakness in wings and legs, and an inability to coordinate muscle movements (Ohlendorf et al. 1978; Eisler 1987; Scheuhammer 1987). Toxic effects in the terrestrial environment have most often resulted from the agricultural use of organomercurial fungicides as seed treatments and in aquatic environments from uses of mercury in the pulp and paper industry and in chlor-alkali plants. Organomercury compounds such as methylmercury are more toxic than inorganic forms, but the inorganic forms may be converted to organomercury through biological and other processes.

Selenium caused mortality of adult and juvenile aquatic birds at a contaminated site in California, but toxic effects have not been observed in marine birds (Ohlendorf et al. 1986, 1988, 1991; Ohlendorf and Fleming 1988; Ohlendorf 1989). Selenium-poisoned adult birds were emaciated, had subacute to extensive chronic hepatic lesions, and had excess fluid and fibrin in the peritoneal cavity. Biochemical changes in their livers included elevated glycogen and non-protein-bound sulfhydryl concentrations and glutathione peroxidase activity but lowered protein, total sulfhydryl, and protein-bound sulfhydryl concentrations. Mean concentrations of selenium in livers, kidneys, and food of affected birds were about 10 times or more those at a nearby reference site.

Mercury and selenium concentrations in the livers of various free-living carnivorous mammals often are highly correlated in a molar ratio that approximates 1:1 (Scheuhammer 1987). However, such a correlation between mercury and selenium in livers of birds is not well established, and the relationship seems highly variable. In diving ducks (scoters and scaup) from San Francisco Bay during 1982, hepatic mercury and selenium were correlated with an overall mercury:selenium molar ratio of 1:6 (Ohlendorf et al. 1986), but not in a subsequent study during 1985 (Ohlendorf et al. 1991). In the latter study, the ratios were typically between 1:7 and 1:15 for scoters from most locations and collection times, but at one site the mean ratio was 1:45.

Elsewhere mercury and selenium concentrations were positively correlated in some bird livers (Furness and Hutton 1979; Hutton 1981; Renzoni et al. 1986), but not others (Leonzio et al. 1986b), or they were negatively correlated (Goede 1985). In one study (Leonzio et al. 1986a), hepatic mercury and selenium were not correlated in Eared Grebes *Podiceps nigricollis* soon after the birds arrived at a mercury-polluted site in autumn, but they were positively correlated in spring when the birds' livers contained higher concentrations of mercury. Selenium concentrations in the grebes collected during three Aprils averaged about 15 µg/g and were about one-third the mercury concentrations in the liver (42–58 µg/g). In contrast, livers of Surf Scoters from San Francisco Bay in 1985 averaged about 60 µg selenium/g and 10 µg mercury/g (Ohlendorf and Fleming 1988). Such differences in relative concentrations are apparently among the important factors affecting selenium–mercury relationships in bird tissues.

Another important factor influencing mercury and selenium relationships in migratory birds may be the relative rates of accumulation for these elements. Selenium and mercury accumulate rapidly in the livers of ducks feeding on high selenium (Heinz et al. 1990) or high mercury (Stickel et al. 1977) diets. In Mallards *Anas platyrhynchos* fed 10 µg selenium/g (as selenomethionine), a plateau level in livers was reached in eight days (Heinz et al., in press). This rapid accumulation to a plateau—and the timing of bird collections—probably determines whether seasonal differences in selenium concentration are observed (Leonzio et al. 1986a; Ohlendorf and Fleming 1988; White et al. 1989). In contrast, the rate of mercury accumulation in bird livers seems to be somewhat slower, perhaps accounting for seasonal differences in mercury and changes in relative molar concentrations of selenium and mercury (Leonzio et al. 1986a; Ohlendorf and Fleming 1988; Ohlendorf et al. 1991).

In the eggs of three species of Hawaiian seabirds, mean molar ratios of mercury:selenium varied between 1:6 and 1:24 and seemed to reflect the exposure of those birds to mercury and selenium (Ohlendorf and Harrison 1986).

2.2.2. *Reproduction*

Excessive amounts of cadmium, lead, mercury, or selenium in the diet can reduce reproductive success of birds (Eisler 1985a, 1985b, 1987, 1988b; Scheuhammer 1987; Ohlendorf 1989), but effects have not been reported for marine birds from the North Pacific. The embryo is often the most sensitive life stage, and hatchability of eggs may be affected by contaminants at concentrations much lower than those that cause observable effects in adult birds. Post-hatching survival of chicks also may be reduced by contaminant burdens they received from the egg, as well as by dietary exposure when they feed in a contaminated environment.

The sample egg technique (Blus 1982) is a good approach for investigating the effects of many environmental contaminants on avian reproduction. This technique determines whether contaminant concentrations in one sample egg from a clutch are related to the fate of other eggs from the same clutch. Custer et al. (1990) reviewed some of the sample studies, most of which focused on organochlorine contaminants, but some included trace elements. One of the basic assumptions of the sample egg approach is that occurrence and concentrations of contaminants are similar among eggs within a clutch (Blus 1982). Available data generally support this assumption, but more information is needed for trace elements. The technique does not work well for those elements (such as cadmium and lead) that do not transfer readily to the egg.

The Mayfield method (Mayfield 1961, 1975) is frequently used to provide statistically testable estimates of nest success and is less biased than traditional methods (see discussion by Ohlendorf et al. 1989). However, the Mayfield method and cause-specific estimates of nest failure usually assess success and failure at a level of nests rather than eggs; thus a nest may be considered successful even if most of the clutch fails to hatch. Aquatic birds affected by environmental contaminants may experience partial clutch failure: although some chicks may hatch from eggs having high concentrations of a particular contaminant, overall success of those nests may be reduced. Therefore, combined measurements of cause-specific nest failure and egg hatchability provide the best means for assessing contaminant-related impairment of reproduction in avian populations. The Mayfield method can be used to make such assessments on an egg basis to determine differences in reproductive success among populations.

Cadmium can reduce egg production by birds when dietary concentrations are high (48–200 µg/g in various studies), but the reproductive effects of low-level cadmium exposure have not been well studied in birds (Scheuhammer 1987). High dietary cadmium ingestion may inhibit calcium absorption in the intestine and cause loss of calcium from the bones. Low-level cadmium exposure may cause delayed testicular development in young birds.

Methylmercury reduces reproductive success at lower doses than those required to produce other pathological effects (Ohlendorf et al. 1978; Eisler 1987; Scheuhammer 1987). Reproductive effects in experimental studies with Mallards and Ring-necked Pheasants *Phasianus colchicus* include decreased egg size, fertility, and hatchability (from embryo mortality), as well as increased early mortality of hatchlings. Pheasants receiving 2–3 µg mercury/g in their diet laid more shell-less eggs than controls, but negligible eggshell thinning was reported in response to organic mercury in other birds. As little as 1 µg methylmercury applied externally to fertile Mallard eggs produced teratogenic effects in developing embryos (Hoffman and Moore 1979). Egg-laying and territorial fidelity of Common Loons *Gavia immer* were negatively related to level of environmental mercury contamination (Barr 1986). Effects were observed when prey contained 0.3–0.4 µg mercury/g (wet weight). In other birds, reproductive effects may occur when mercury concentrations in eggs are about 2 µg/g wet weight (Eisler 1987).

Levels of lead below 100 µg/g in the diet usually cause few significant reproductive effects in birds, but effects are species specific (Scheuhammer 1987). For example, 10 µg lead/g in the diet of Japanese Quail *Coturnix japonica* caused significant reduction in plasma calcium level and egg production, but over 200 µg lead/g was required to cause similar effects in chickens. In general, young altricial birds seem to be more susceptible than adult birds or young precocial birds (Eisler 1988b).

Avian embryos are very sensitive to the toxic effects of selenium (Ohlendorf 1989). Hatchability of fertile eggs is considered the most sensitive measure of selenium toxicity and is reduced in chicken, quail, and duck eggs when dietary concentrations are 6–9 µg/g. Fertility is not affected, but selenium causes high rates of embryo mortality and developmental abnormalities (i.e., teratogenicity) in birds. The abnormalities typically include multiple defects of the eyes, legs, beak, and cranium, which may be malformed or missing. In aquatic birds, reproductive effects of selenium have been observed in field studies at several sites contaminated with selenium from agricultural wastewater (Ohlendorf 1989; Ohlendorf et al. 1989; Ohlendorf and Skorupa 1989; Skorupa and Ohlendorf 1991). In Mallards, diets containing 8 µg selenium/g (as selenomethionine) and those containing 16 µg/g caused malformations in 6.8% and 67.9% of unhatched eggs, respectively, compared with 0.6% for controls (Heinz et al. 1989). Reduced survival and growth occurred in ducklings whose parents had received 8 or 16 µg selenium/g, even though all ducklings were fed a control diet. Heinz et al. (1989) concluded that the dietary threshold of selenium, as selenomethionine, necessary to impair reproduction is between 4 and 8 µg/g.

2.2.3. *Behaviour*

Behavioural effects of cadmium, mercury, and selenium at environmentally realistic dietary concentrations have been studied in ducks, but I have found no report of such studies in marine birds.

Pairs of adult American Black Ducks *Anas rubripes* were fed a diet containing 0, 4, or 40 µg cadmium/g (Heinz et al. 1983). One-week-old ducklings that had been fed the same dietary concentrations of cadmium as their parents were tested for avoidance of a fright stimulus. Ducklings fed 4 µg cadmium/g ran significantly farther from the stimulus than did controls or ducklings fed 40 µg/g. Such an alteration in behaviour could have harmful effects on wild birds. Reasons for the hyperresponsiveness of ducklings fed 4 µg/g but normal behaviour by those receiving 40 µg/g are unknown.

Three generations of Mallards were fed either a control diet or a diet containing 0.5 µg mercury/g in the form of methylmercury (Heinz 1979). The levels of mercury in adult tissues and eggs remained about the same over three generations. Females fed a diet containing 0.5 µg mercury/g laid a greater percentage of their eggs outside their nestboxes than controls and also laid fewer eggs and produced fewer ducklings. Ducklings from parents fed methylmercury were less responsive than controls to tape-recorded maternal calls, but were hyperresponsive to a frightening stimulus in avoidance tests; there were no significant differences in locomotor activity in an open-field test.

Pairs of adult Mallards were fed a control diet or a diet containing 1, 2, 4, or 8 µg selenium/g in the form of selenomethionine (Heinz and Gold 1987). Ducklings from these pairs were fed an untreated diet from hatching through six days of age, at which time their avoidance of a fright stimulus was tested. Selenium had no effect on the ducklings' response to the fright stimulus.

3. Conclusions and recommendations

Effects of environmental contaminants on marine birds of the temperate North Pacific have not been studied comprehensively. However, based on studies in the North Pacific and in the field and laboratory elsewhere, I reached the following conclusions and recommendations:

(a) Trace elements are not likely to produce mortality through their acute effects in marine birds under current conditions. An exception is the ingestion of paint chips by albatross fledglings on Midway Atoll.

(b) Chronic toxicity of trace elements does occur through direct effects in the birds and indirect effects on their habitat. These effects warrant further study, particularly:

1. Histopathological and other indicators of tissue damage resulting from environmental contaminants.
2. Reproductive success, notably egg hatchability and cause-specific nest failures.
3. Possible interactions among trace elements, such as mercury and selenium or cadmium and zinc, that may affect their absorption and toxicity. The interrelationships between mercury and selenium in marine birds are of interest because concentration ratios are highly variable and not consistent with findings in marine mammals.

(c) Further sampling is needed to determine geographic patterns of trace element occurrence in birds of the North Pacific and to monitor temporal trends in concentrations of these chemicals in bird tissues. Sampling should include pelagic species and species feeding near shore and in estuaries.

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