Source ID #119

LAKE AND RESERVOIR MANAGEMENT, 1988 4(2): 175–180
© 1988 NORTH AMERICAN LAKE MANAGEMENT SOCIETY

Reproduction in Black-Crowned Night-Herons Fed Selenium

1/1/88 Rec 0025

Gregory J. Smith
Gary H. Heinz
David J. Hoffman
James W. Spann
Alexander J. Krynitsky
U. S. Fish and Wildlife Service, Patuxent Wildlife Research Center, Laurel, MD 20708

ABSTRACT

Agricultural and industrial practices can produce wastewater that contains high concentrations of selenium, a naturally-occurring trace element. Selenium entering aquatic systems through wastewater inflow can accumulate in aquatic food chains to levels that may be toxic to fish and wildlife species. Mallard reproduction is known to be adversely affected by 10 ppm selenium in the diet (containing 7-10 percent moisture, in the form of selenomethionine); however, hatching success of eggs laid by black-crowned night-herons fed a 10 ppm selenium diet, as selenomethionine, in this study was not different from eggs laid by herons fed an unsupplemented diet (0.1 ppm selenium). Organ weights, hemoglobin concentrations, hematocrits, eggshell thickness, and shell thickness did not differ between controls and herons receiving 10 ppm selenium. Developmental malformations commonly associated with selenium exposure in other birds were not observed in heron embryos or hatchlings in the 10 ppm group. However, three-day-old hatchlings from herons fed 10 ppm selenium had shorter radius-ulna and femur lengths and higher liver malondialdehyde concentrations than controls. Selenium residues in heron eggs were lower than those reported in mallards fed the same amount of selenium. Results of this study suggest that herons are less sensitive to the toxic effects of selenium than mallards. Other hypotheses are also considered to explain the different responses of the two species.

Introduction

Selenium, a naturally-occurring trace element, has been identified recently as an important potential environmental contaminant in aquatic systems (Maier et al. 1988; Ogle et al. 1988). Studies conducted with mallard ducks (*Anas platyrhynchos*) have shown that environmentally realistic concentrations of selenium in aquatic food chains in some areas are sufficient to impair reproduction. This paper reports the results of a study conducted to determine the effects of selenium on black-crowned night-heron reproduction and to compare the sensitivity of this species to that of mallards.

High selenium concentrations in power plant fly ash reservoirs have affected fish populations severely (Lemly, 1985). Agricultural drainwater is another major source of environmental selenium exposure to fish and wildlife. In 1983, high rates of embryo deformities and poor reproduction of aquatic birds were found at the Kesterson National Wildlife Refuge in California's San Joaquin Valley (Ohlendorf et al. 1986a). Selenium concentrations in food organisms from the Kesterson Refuge ranged from 22 to 175 ppm on a dry weight basis (Ohlendorf et al. 1986a). Contamination was linked to selenium in irrigation drainwater supplied to Kesterson (Ohlendorf et al. 1986a, b).

9467

The discovery of selenium contamination at the Kesterson Refuge and early studies demonstrating that selenium affected hatching success of chicken eggs (Poley and Moxon, 1938) prompted recent studies with mallards. Mallard hens fed a diet supplemented with 25 ppm selenium in the form of sodium selenite produced fewer ducklings than controls (Heinz et al. 1987). Mallards fed a diet supplemented with 10 ppm selenium in the organic form of selenomethionine (dry mash diet containing 7-10 percent water) also produced fewer young and had a higher incidence of abnormal embryos than controls (Heinz et al. 1987). Selenium concentrations greatly exceeding this 10 ppm level have been found in wildlife food organisms in California wetlands, and it is now apparent that environmentally occurring concentrations of selenium can affect waterfowl reproduction. Little is known about differences in sensitivity among avian species to selenium poisoning. All eggs laid by chickens fed a grain diet containing 10 ppm selenium failed to hatch (Poley and Moxon, 1938). Japanese quail (*Coturnix japonica*) fed 6 or 12 ppm selenium as sodium selenite also had reduced hatching success (El-Begearmi et al. 1977). Mallards were less sensitive to the effects of selenium as sodium selenite than chickens (Arnold et al. 1973) and Japanese quail (El-Begearmi et al. 1977). Differences in species sensitivity are important in assessing the environmental hazard of selenium to wildlife populations. One species, the black-crowned night-heron (*Nycticorax nycticorax*), has a diet that is very different from that of mallards. Herons represent a group of birds that could easily be exposed to selenium poisoning through aquatic food chains; herons also represent an important feeding guild in a wetland community. Therefore, this study concerns the effects of selenium on black-crowned night-heron reproduction and was done in a way that we could directly compare the response of this species could be directly compared to that of mallards.

Methods

Black-crowned night-herons were obtained from a captive breeding colony at the Patuxent Wildlife Research Center in Laurel, Maryland. Adult pairs were housed in 3 m X 14 m pens and were randomly assigned to one of three dietary treatments. Five pairs received a control (unsupplemented) diet and five pairs received a diet supplemented with 10 ppm selenium. Two additional pairs and two unpaired females, not included in the reproductive study, received a 30 ppm selenium diet. Diets were prepared by dissolving seleno-DL-methionine (98-99 percent pure, Sigma Chemical Co., St. Louis, Mo.) in distilled-deionized water and mixing this solution in Nebraska Bird-of-Prey diet (Animal Spectrum Inc., Lincoln, Neb). The control diet received only distilled-deionized water to maintain an equal moisture content among diets. Selenium recoveries in the feed samples analyzed resembled those reported for mallard diets from a previous study (Heinz et al. 1987). The control diet had an average selenium concentration of 0.1 ppm (dry weight).

Selenomethionine was added to the heron diets to yield 10 and 30 ppm selenium when the moisture content of the diet was equilibrated to the moisture content of the mallard diet (7-10 percent). Mixing the diets by this method resulted in a 10 ppm selenium diet fed to herons that was equivalent to the 10 ppm selenium diet fed to mallards in a previous study (Heinz et al. 1987). Both the 10 and 30 ppm diets represent concentrations that are almost 91 percent of an actual dry weight based diet. Therefore, for convenience these dietary concentrations will be referred to as 10 and 30 ppm selenium in this paper.

All adult females were permitted to lay one full clutch of eggs prior to testing (these were removed upon completion); the male and female were then placed on their assigned experimental diet. This procedure increased the percentage of fertile eggs and allowed herons to receive selenium-treated or control diets before reinitiation of egg laying. This method differs from that used for mallards, which generally have much higher egg fertility than did the captive herons.

The first egg was laid on March 17, 1985, and all herons were necropsied at the termination of the study on June 19, 1985. At this time all females had laid at least 14 eggs for incubation. The average number of days that herons were on 10 ppm and 30 ppm selenium diets prior to laying their first egg was 13 and 23 days, respectively. The mean number of days on treatment prior to necropsy was 92. All eggs laid after treatment began were collected daily, labeled, and stored at 10° to 13°C. The first egg and every fifth egg laid thereafter were saved for selenium analysis to determine within-clutch variation of selenium residues. Among-clutch comparisons were made with the sixth egg. All eggs not saved for selenium analysis (between 14 and 29 eggs per pair) were transferred weekly to an incubator maintained at 37°C and 70 percent humidity. Eggs were candled at weekly intervals to determine embryo viability and fertility.

Embryos that died during incubation and hatchlings were examined for external, soft tissue, and skeletal deformities (Hoffman et al. 1982). All embryos that hatched were monitored for 72 hours after hatch to determine survival. The yolk sac served as the only source of nutrition for hatchlings during this period. Most of the mortality observed in mallard ducklings during the earlier study with selenomethionine (Heinz et al. 1987) occurred within three days after hatch. Therefore, this period was selected for monitoring heron hatchling survival. Skeletal measurements were made using alizarin red-S stained skeletal preparations of hatchlings (Hoffman et al. 1982). Hematocrit and hemoglobin concentrations were determined for hatchlings (Hoffman et al. 1982), and liver tissue samples were prepared for malondialdehyde determinations as a measure of lipid peroxidation (Aust, 1985).

Adult herons were weighed when initially given experimental diets and again at necropsy. Hatchlings were sacrificed at 72 hours post-hatch, and blood and liver samples were obtained. Blood samples and liver, kidney, spleen, and body weights were obtained from adult herons at necropsy. The contents of eggs, as well as livers from adult herons, were stored frozen in acid-cleaned jars. Eggshells were rinsed with water and air-dried at least one month prior to measuring shell thickness and weights for determining the Ratcliffe Index of eggshell quality (Ratcliffe, 1967).

All samples analyzed for selenium were homogenized and digested using nitric acid and hydrogen peroxide according to the procedure developed by Krynitsky (1987). Following sample preparation, selenium concentrations were quantified using graphite furnace atomic absorption spectro-metry (Krynitsky, 1987). The lower limit for reporting residues was 0.05 ppm (wet weight). Selenium concentrations in eggs and livers are reported on a wet weight basis that can be converted to a dry weight basis by using the mean moisture content of 80 and 69 percent for eggs and livers, respectively.

Reproductive data were subjected to an angular transformation (Sokal and Rohlf, 1973) prior to one-way analysis of variance ($P \leq 0.05$). The Tukey's multiple comparison procedure ($P \leq 0.05$) was used when separating three or more means. Selenium concentrations were log-transformed prior to statistical analysis.

Results

Hatching success of fertile eggs laid by herons on the 10 ppm selenium diet did not differ significantly from controls (Table 1). Both male and female herons fed the 30 ppm selenium diet lost more weight than herons fed the 10 ppm or control diets (Table 2), suggesting a possible aversion to the selenium-treated diets or perhaps illness caused by the selenium treatment. None of the herons died or showed signs of selenium toxicosis. Liver, heart, or spleen weights did not differ among adult herons fed control, 10 ppm, or 30 ppm selenium diets. Hemoglobin concentrations, hematocrits, egg fertility, eggshell thicknesses, and the Ratcliffe Index of eggshell quality were not affected by selenium treatment in adults.

Table 1.—Mean reproductive parameters (± SD) for black-crowned night-herons maintained on a diet supplemented with 0 or 10 parts per million selenium, in the form of selenomethionine.

SELENIUM (ppm) ADDED TO DIET	N[1]	HATCHING SUCCESS OF FERTILE EGGS (%)[2]	INFERTILE EGGS (%)
0 (control)	5	32.2 ± 21.8 a[3]	24.6 ± 14.7 a
10	5	43.9 ± 13.8 a	14.9 ± 15.9 a

[1] Number of breeding pairs.
[2] Using artificial incubation.
[3] Means sharing the same letter within one column were not significantly different at $P \leq 0.05$ using one-way analysis of variance. Statistical comparisons were performed on data subjected to an angular transformation.

Black-crowned night-heron hatchlings produced from pairs fed 10 ppm selenium showed no soft tissue, external, or skeletal deformities, although three-day-old hatchlings had shorter femur and radius-ulna lengths (Table 3). Hematology of hatchlings appeared unaffected by selenium treatment; however, liver concentrations of malondialdehyde were higher in hatchlings from the 10 ppm selenium group (Table 3).

Table 2.—Mean weight loss (± 1 SD) in black-crowned night-herons maintained on diets supplemented with selenium in the form of selenomethionine.

SELENIUM (ppm) ADDED TO DIET	MEAN WEIGHT LOSS[1] (g)			
	N	FEMALES	N	MALES
0 (control)	5	31.6 ± 20.4 a[2]	5	20.2 ± 82.4 a
10	5	74.4 ± 28.6 ab	5	36.2 ± 72.8 a
30	4	124.2 ± 85.5 b	2	270.0 ± 11.3 b

[1] Weight loss between the time of treatment onset and sacrifice (19 June 85). Four males, two control and two fed the 10 ppm diet, gained weight (range 4 to 98 g.)
[2] Means sharing the same letter within one column were not significantly different using analysis of variance and the Tukey's multiple comparison procedure. A significant ($P = 0.028$) interaction between treatment and sex was determined indicating the pattern of weight loss was different for males and females.

Table 3.—Morphological, hematological, and biochemical parameters (means ± SE) in 3-day-old black-crowned night-herons hatched from eggs laid by females fed a control diet or a diet supplemented with selenium, in the form of selenomethionine.

PARAMETER	0 ppm (CONTROLS) N = 16	10 ppm SELENIUM N = 24
Weight (g)	21.0 ± 1.1	20.9 ± 0.9
Liver weight (g)	0.60 ± 0.03	0.59 ± 0.03
Humerus length (mm)	11.1 ± 0.1	10.8 ± 0.1
Radius-ulna length (mm)	11.3 ± 0.2	10.6 ± 0.1*
Femur length (mm)	15.7 ± 0.2	15.1 ± 0.2*
Tibiotarsus length (mm)	19.4 ± 0.3	19.0 ± 0.2
Hematocrit (%)	29.9 ± 1.3	28.2 ± 0.9
Hemoglobin (g/dl)	7.9 ± 0.2	8.0 ± 0.3
Liver malondialdehyde (nmol/g)	18.3 ± 1.2	26.2 ± 3.6*

* Different from controls at $P \leq 0.05$.

Concentrations of selenium in the sixth egg laid and in adult livers were related to dietary levels (Table 4). Concentrations of selenium in adult male livers were significantly greater than in females (Table 4). Selenium concentrations among eggs within one clutch varied little with an average coefficient of variation of 16 percent for five females fed 10 ppm selenium and two females fed 30 ppm selenium (Table 5).

Discussion

Results of this study suggest that reproduction of black-crowned night-herons is less sensitive to the effects of selenium than that of mallards. An earlier study of mallards concluded that they were less sensitive to the effects of sodium selenite than chickens (Heinz et al. 1987). Hatching success of fertile eggs laid by black-crowned night-herons fed 10 ppm selenium did not differ from herons fed a control diet. Moreover, no developmental malformations occurred in heron embryos that failed to hatch or in hatchlings. All hatchlings survived the 72-hour post-hatch period in both the control and 10 ppm selenium groups. One adult female heron fed 30 ppm selenium laid eight fertile eggs; two of these hatched, producing normal chicks that survived the 72-hour period.

Mallards fed an equivalent 10 ppm selenium diet (Heinz et al. 1987) had lower survival of young and a greater incidence of abnormal embryos (Table 6). Most mortality of young mallards was observed during the first few days after hatch; therefore, survival of young herons was monitored during the most critical period following hatch. The teratogenic effects of selenium in mallard embryos included hydrocephaly, bill and eye defects, and malformations of the legs, feet, and toes. None of these effects was observed in heron embryos, although hatchlings had shorter radius-ulna and femur lengths than controls. Liver malondialdehyde concentrations were elevated in black-crowned night-heron hatchlings in the 10 ppm selenium group, suggesting some selenium-induced oxidant activity, manifested as hepatic liver peroxidation. A similar effect has been reported for mallard ducklings exposed to selenium (Hoffman and Heinz, 1987).

Adult herons in all of the experimental groups lost weight except for two males in the control group and two males in the 10 ppm selenium group that gained weight. Weight loss of herons fed the 30 ppm selenium diet was greater than for those fed either the 10 ppm selenium or control diets. Males fed 30

Table 4.—Geometric mean selenium concentrations (ppm, fresh-weight basis) in eggs and livers of black-crowned night-herons fed selenium in the form of selenomethionine. Concentration ranges and sample sizes (n) are given in parentheses.

SELENIUM ADDED TO DIET (ppm)	EGG CONCENTRATION[1]	LIVER CONCENTRATION FEMALE	LIVER CONCENTRATION MALE
0 (control)	0.56 (0.44-0.66; n = 5) a[2]	0.62 (0.46-0.78; n = 5) a	1.1 (0.86-1.2; n = 5) a
10	3.3 (2.7-3.6; n = 5) b	4.2 (3.4-5.2; n = 5) b	5.1 (3.8-7.0; n = 5) b
30	9.2 (8.9-9.6; n = 2) c	13 (12-16; n = 4) c	17 (11-25; n = 2) c

[1] Eggs sampled were the sixth egg laid.

[2] Means sharing the same letter within each column were not significantly different at $P \leq 0.05$ using one-way analysis of variance (on log-transformed data) with the Tukey's multiple comparison procedure. Liver residues were significantly ($P \leq 0.05$) greater in male herons than in females.

Table 5.—Intra-clutch variability of selenium concentrations (ppm, fresh-weight basis) in sequentially-laid black-crowned night-heron eggs from herons fed diets supplemented with 10 and 30 ppm selenium, in the form of selenomethionine.

SELENIUM ADDED TO DIET (ppm)	PEN NO.	EGG NUMBER 1	6	11	16	21	26	31	36	N	$\bar{x}$	SD	CV[1]
		ppm											
10	1	2.9	3.6	3.6	2.6	2.7	2.3	2.7	NA[2]	7	2.9	0.5	17.2
	2	3.6	3.6	3.2	2.9	NA	NA	NA	NA	4	3.3	0.3	10.2
	3	2.9	3.5	3.6	2.9	2.9	3.0	3.2	NA	7	3.1	0.3	9.5
	4	2.8	2.7	3.3	3.3	3.7	NA	NA	NA	5	3.2	0.4	13.0
	5	3.2	3.3	4.4	3.8	3.9	3.9	3.1	3.7	8	3.7	0.4	11.9
30[3]	6	7.8	9.6	NA	7.6	NA	NA	NA	NA	3	8.3	1.1	8.3
	7	3.5	8.9	7.2	NA	NA	NA	NA	NA	3	6.5	2.8	42.3

[1] Coefficient of variation (%), CV = SD X 100/$\bar{x}$.
[2] NA; not analyzed because not all herons laid up to 36 eggs. The eleventh egg for pen No. 6 was not analyzed because it was cracked.
[3] Two additional females in the 30 ppm group did not lay any eggs.

ppm selenium lost more weight than females; however, none of the herons showed overt signs of selenium poisoning. No differences in hemoglobin concentrations, hematocrits, or organ weights of adults were related to selenium exposure.

Selenium concentrations in eggs and livers of black-crowned night-herons increased as dietary selenium concentrations increased, a finding similar to that for mallards fed sodium selenite (Heinz et al. 1987). Selenium in livers of male herons was greater than in females, suggesting elimination of selenium through egg laying as documented in mallards and Japanese quail (Stoewsand et al. 1978; Heinz et al. 1987). Selenium concentrations varied little within clutches, suggesting that an egg sampled from a clutch adequately represents selenium concentrations in other eggs in the clutch; however, this may be the case only when the selenium concentration in the diet of the female is constant during the laying period. Eggshell thickness and the Ratcliffe eggshell index were not affected by selenium treatment. Mallard eggshell thickness also was not altered by selenium treatment (Heinz et al. 1987).

Dietary concentrations of selenium were the same for both species; however, herons were fed a meat-based moist diet whereas mallards received a dry grain-based diet. Total protein of the two diets was similar (17 percent for duck mash versus 19 percent for heron diets) on a fresh weight basis, although the heron diet contained about 60 percent moisture. Under some circumstances, increasing the protein content, specifically methionine (when administering selenomethionine), may have protected against selenium toxicity (Rosenfeld and Beath, 1964). Vitamin E has antioxidant activity, preventing the formation of free radicals and peroxides (Noguchi et al. 1973), and has been demonstrated to protect against methylmercury toxicity (Ganther, 1980). However, it is unlikely that the heron diets contained an excess of vitamin E or that the vitamin E content would be high enough to combat selenosis. Nutritional analysis of the heron diet suggests that vitamin E likely was present in a moderate concentration and not excessive compared with nutritional requirements.

The number of days on selenium treatment prior to egg laying in herons fed a 10 ppm selenium diet was 13 days compared with 41 days for mallards (Heinz et al. 1987). Although the resulting selenium concentrations in heron eggs were lower than those for mallards fed an equivalent selenium diet ($t = 2.43$; $df = 8$; $P \leq 0.05$), this difference represents a reduction of only 1.3 ppm selenium (wet weight) and is based on a small number of eggs. Moreover, the low variability of selenium concentrations within heron clutches suggests that selenium concentrations had

Table 6.—Comparison of effects of dietary selenium in black-crowned night-herons and mallards. Both species were fed diets with equivalent selenium concentrations (10 ppm selenium, in the form of selenomethionine). Data for mallards are from Heinz et al. (1987).

PARAMETER	SPECIES: MALLARD	BLACK-CROWNED NIGHT-HERON
Hatchling survival and productivity	Reduced[1]	Not Affected
Percent of eggs with abnormal embryos	18.3%	None Observed
Mean selenium in eggs (ppm, wet weight)	4.6	3.3
Mean selenium in male livers (ppm, wet weight)	8.6	5.2
Mean selenium in female livers (ppm, wet weight)	4.7	4.3

[1] Mallard hatchling survival to 21 days was reduced from 98.7% for controls to 50% for the 10 ppm selenium group and number of young produced reduced from 9.7 young per hen for controls to 2.0 young per hen for the 10 ppm selenium group.

reached an equilibrium. If the small difference in selenium concentrations between herons and mallards actually resulted in the different responses of the two species, then the concentration response curve would be extremely steep, indicating an abrupt threshold. It is more likely that heron embryos are less sensitive to selenium than mallard embryos. Species differences in sensitivity to selenium toxicosis have been previously reported. Mallards are less sensitive to sodium selenite (Heinz et al. 1987) than chickens or Japanese quail. No chicken eggs hatched when hens were fed a 10 ppm selenium diet formulated from a selenium-rich grain (Poley and Moxon, 1938).

Herons are far removed taxonomically from waterfowl or gallinaceous birds used in previous studies. Selenium concentrations in livers of male herons and eggs were lower than those found in mallards fed an equivalent selenium diet. Differences in absorption or excretory efficiencies of selenium resulting from different gastrointestinal morphology and physiology of the two species could explain differences in selenium concentrations. However, the apparent lower sensitivity of herons could also be due to a difference in the distribution of selenium within the egg, the chemical form of the protein-bound selenium, or other factors.

Before this study the mallard was the only avian species used other than chickens or quail to evaluate the potential hazard of selenium to birds inhabiting contaminated wetlands. Although herons appear less sensitive to selenium than mallards, many other species of aquatic birds and waterfowl may be exposed to environmental concentrations of selenium that impair mallard reproduction (Ohlendorf et al. 1986b). Concentrations of selenium found in aquatic organisms at Kesterson Reservoir greatly exceed those known to affect reproduction and survival of some avian species.

High selenium levels in food chains have the potential to markedly alter wildlife community structure in contaminated wetlands. Differential contamination of aquatic communities, e.g., plant or invertebrate components of food chains, could lead to different wildlife species being exposed to selenium. Moreover, differences in species' sensitivity to selenium could influence which taxa are able to tolerate selenium exposure and persist in contaminated environments. The absence of sensitive species or a notable reduction in community complexity may provide signs of selenium contamination of aquatic systems. More research is needed to determine the differences in sensitivity of various species and to define the overall potential impact that selenium contamination of avian food chains may have on populations.

ACKNOWLEDGEMENTS: We thank J. Armstrong, P. McDonald, and D. Wallace for typing the manuscript, and T. Erlandson for help with the study. We also thank L. Blus and E. Flickinger for reviewing the manuscript and H. Ohlendorf for suggesting the need for this study.

References

Arnold, R. L., O. E. Olson, and C. W. Carlson. 1973. Dietary selenium and arsenic additions and their effects on tissue and egg selenium. Poultry Sci. 52:847-54.

Aust, S. D. 1985. Lipid peroxidation. Pages 203-207 in R. A. Greenwald, ed. CRC Handbook of Methods for Oxygen Radical Research. CRC Press, Boca Raton, FL.

El-Begearmi, M. M., M. L. Sunde, and H. E. Ganther. 1977. A mutual protective effect of mercury and selenium in Japanese quail. Poultry Sci. 56:313-22.

Ganther, H. E. 1980. Interactions of vitamin E and selenium with mercury and silver. Annals N.Y. Acad. Sci. 355:212-26.

Heinz, G. H., D. J. Hoffman, A. J. Krynitsky, and D. M. G. Weller. 1987. Reproduction in mallards fed selenium. Environ. Toxicol. Chem. 6:423-33.

Hoffman, D. J. and G. H. Heinz. 1987. Developmental toxicity of excess selenium in mallard (Anas platyrhynchos) ducks. Fed. Proc. 46:1154.

Hoffman, D. J., W. C. Eastin, and M. L. Gay. 1982. Embryotoxic and biochemical effects of waste crankcase oil on bird's eggs. Toxicol. Appl. Pharmacol. 63:230-41.

Krynitsky, A. J. 1987. Preparation of biological tissue for determination of arsenic and selenium by graphite furnace atomic absorption spectrometry. Anal. Chem. 59:1884-6.

Lemly, A. D. 1985. Toxicology of selenium in a freshwater reservoir:implications for environmental hazard evaluation and safety. Ecotoxicol. Environ. Safety 10:314-38.

Maier, K.J., R.S. Ogle, and A.W. Knight. 1988. The selenium problem in lentic systems. Lake Reserv. Manage. 4(2): This volume.

Noguchi, T., A. H. Cantor, and M. L. Scott. 1973. Mode of action of selenium and vitamin E in prevention of exudative diathesis in chicks. J. Nutr. 103:1502.

Ogle, R.S. et al. 1988. Bioaccumulation of selenium in aquatic ecosystems. Lake Reserv. Manage. 4(2): This volume.

Ohlendorf, H. M., D. J. Hoffman, M. K. Saiki, and T. W. Aldrich. 1986a. Embryonic mortality and abnormalities of aquatic birds: apparent impacts of selenium from irrigation drainwater. Sci. Total Environ. 52:49-63.

Ohlendorf, H. M. et al. 1986b. Relationships between selenium concentrations and avian reproduction. Trans. 51st N. Am. Wildl. Nat. Res. Conf. 51:330-42.

Poley, W. E. and A. L. Moxon. 1938. Tolerance levels of seleniferous grains in laying rations. Poultry Sci. 17:72-6.

Ratcliffe, D. A. 1967. Decrease in eggshell weight in certain birds of prey. Nature 215:208-10.

Rosenfeld, I. and O. A. Beath. 1964. Selenium: Geobotany, Biochemistry, Toxicity, and Nutrition. Academic Press, New York.

Sokal, R. R. and F. J. Rohlf. 1973. Introduction to Biostatistics. W. H. Freeman and Co., San Francisco.

Stoewsand, G. S., W. H. Gutenmann, and D. J. Lisk. 1978. Wheat grown on fly ash: high selenium uptake and response when fed to Japanese quail. J. Agric. Food Chem. 26:757-9.