

## Environmental Contaminants and Nesting Behavior of Great Blue Herons from the Columbia and Willamette Rivers, Oregon and Washington

### Abstract

Reduced productivity and elevated contaminant concentrations have been documented in fish-eating birds, including bald eagles, from the Columbia River since 1984. To determine whether nest attendance was related to contaminant concentrations in eggs of fish-eating birds, we examined breeding behavior of great blue herons at six colonies, in Oregon and Washington. We chose great blue herons as an indicator species for the effects of environmental contaminants on the guild of fish-eating birds because previous studies have demonstrated their utility. Patterns of attendance and nest visitation were significantly different among sites. The site with the highest concentrations of *p,p'*-DDE and total PCBs had significantly lower nest attendance relative to the reference site. Differences in nest attendance among colonies were inversely related to *p,p'*-DDE and PCB concentrations; however fledging and reproductive success in all colonies were similar to those reported for healthy populations. Differences in nest attendance and visitation among sites did not appear to be affecting nestling survival pre-fledging.

### Introduction

Altricial nestlings have three main requirements that must be met to insure their survival: protection, thermoregulation, and nutrition (Gill 1990). Protection of eggs and nestlings requires an adult to be present and defend the nest. Thermoregulation of eggs and chicks also requires nest attendance, and the adults must display proper incubation and brooding behaviors. Adults must also satisfy the daily energy requirements of their chicks by presenting a sufficient quantity and quality of food items, which requires a certain number of nest visits and proper feeding behaviors. Therefore, nest attendance is critical to successful reproduction. If a breeding pair does not meet these basic requirements, their reproductive success may be impaired.

In addition to direct mortality and teratogenicity, contaminants can have sublethal effects on the behavior of vertebrates. Organochlorine compounds (OC) have been implicated in abnormal breeding behavior in several bird species. Reduced nest attentiveness, nest defense, and hatch success in herring gulls (*Larus argentatus*), mallards (*Anas platyrhynchos*), merlins (*Falco columbarius richardsonii*), and ring doves (*Streptopelia risoria*)

have been associated with elevated concentrations of DDE, PCBs, and other organochlorine pesticides (Keith 1966, Peakall and Peakall 1973, Fyfe et al. 1976, Fox et al. 1978, McArthur et al. 1983). Ring doves exposed to DDE also spent less time engaged in courtship activities and had delayed renesting and reduced clutches in renesting attempts (Haegle and Hudson 1973, 1977). Elevated levels of PCB, polychlorinated dibenzo-p-dioxins (PCDD) and polychlorinated dibenzo-furans (PCDF) were detected in eggs of Forster's terns (*Sterna forsteri*) and implicated in shorter incubation periods and lower reproductive success relative to an uncontaminated site (Kubiak et al. 1989).

Residues of OC and PCB have been documented in many species of piscivorous birds, mammals, and fish from the Columbia and Willamette rivers in Oregon and Washington (Blus et al. 1980, Henny et al. 1984, Fitzner et al. 1988, Schmitt et al. 1990, Parsons et al. 1991, Anthony et al. 1993, Henny et al. 1996). In the 1970s, PCB residues in mink (*Mustela vison*) and river otter (*Lutra canadensis*) from the Columbia River (Henny et al. 1981) exceeded concentrations known to cause total reproductive failure in laboratory studies (Platonow and Karstad 1973). Egg concentrations of DDE were associated with reduced productivity in bald eagles (*Haliaeetus leucocephalus*), and eggshell thinning in both nesting eagles and black-crowned night herons

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(*Nycticorax nycticorax*) along the Columbia River (Henny et al. 1984, Anthony et al. 1993). Residues of PCB and *p,p'*-DDE (DDE) were detected in all life stages of bald eagles during the 1980s (Anthony et al. 1993), which strongly implicated the Columbia River as a primary source of these contaminants.

Several contaminants including polychlorinated dibenzo-*p*-dioxins (PCDDs), DDE, and PCBs have been found at potentially hazardous concentrations in fish and wildlife from the Columbia and Willamette rivers. Studies conducted by the U.S. Environmental Protection Agency (1992) detected in some fish tetrachlorodibenzo-*p*-dioxin residues that exceeded guidelines for the protection of human health and resulted in the issuance of a total maximum daily load (TMDL) for dioxin in both rivers. Fish collected from the Portland Harbor of the Willamette River exhibited strongly induced cytochrome P450 1A1, which is indicative of exposure to TCDD (Curtis et al. 1993). PCDD concentrations in unhatched bald eagle and double-crested cormorant (*Phalacrocorax auritus*) eggs collected from the Columbia River Estuary (Anthony et al. 1993, U.S. Fish and Wildlife Service 1999) were similar to concentrations found in fish-eating birds from Michigan that had poor reproductive success (Kubiak et al. 1989). Since 1984, bald eagle productivity along the Columbia River has been reduced and has been associated with elevated concentrations of DDE and PCBs in eggs and carcasses (Anthony et al. 1993).

Although Anthony et al. (1993) associated contaminants with reduced bald eagle productivity along the Columbia River, they were not able to determine the factors responsible for the reduced productivity. Further evaluation of contaminant effects on piscivorous birds in the Columbia River systems was needed, but a replacement or surrogate species was needed in any additional studies to avoid additional impacts to bald eagles, which are listed under the Endangered Species Act as a threatened species. Previous studies demonstrated the utility of great blue herons (*Ardea herodias*) as an indicator species for contaminants in piscivorous birds (Elliot et al. 1989, Whitehead 1990), and have reported on productivity and nesting behaviors in areas not impacted by contaminants (Pratt 1970, McAloney 1973, Dowd and Flake 1984, Butler 1992). Therefore, we chose to use great blue herons as an indicator species

for the effects of environmental contaminants on bald eagles and other piscivorous birds in the Columbia River system.

The purpose of this study was to determine whether environmental contaminants were elevated in great blue herons and whether contaminant concentrations were associated with adult behaviors potentially responsible for reduced productivity. We previously reported on the contaminant concentrations in eggs of great blue herons and on reproductive parameters likely to be directly impacted by elevated contaminant concentrations (Thomas and Anthony 1999). We now report on behavioral responses that may be influenced by environmental contaminants: patterns of nest attendance and nest visitation by adult great blue herons in northwest Oregon and Washington. We investigated whether patterns of parental nest attendance were different at contaminated sites versus an uncontaminated site, and whether among-site differences in parental nest attendance were related to contaminant concentrations in eggs. We focused on the presence of adults at the nest and the rate of nest visitation as measures of nest attendance and feeding rates, respectively.

### Study Area

Study sites were located in northwest Oregon and Washington (Figure 1). The colonies at Bachelor, Fisher, and Karlson islands were located on the lower Columbia River. Bachelor Island was 6.4 km upstream from a pulp and paper mill, and Fisher Island was 3.2 km downstream from the same mill. Karlson Island was in the Columbia River Estuary, 27.2 km downstream from the closest pulp and paper mill. The Molalla State Park and Ross Island colonies were located on the lower Willamette River. Molalla was 16 km upstream from the nearest pulp and paper mill; Ross Island was 22.4 km downstream. The reference site, Samish Island, was in Puget Sound, Washington, 60.8 km downstream from the nearest pulp and paper mill. We designated Samish as the reference site due to a previous study that detected low concentrations of most OC in heron eggs from that colony (Cobb et al. 1994). Average annual precipitation is 108 cm along the Columbia and Willamette rivers and 85 cm near Samish Island in the Puget Sound (Franklin and Dyrness 1988).

Karlson and Samish islands were in the transition zone between fresh and saltwater, and the

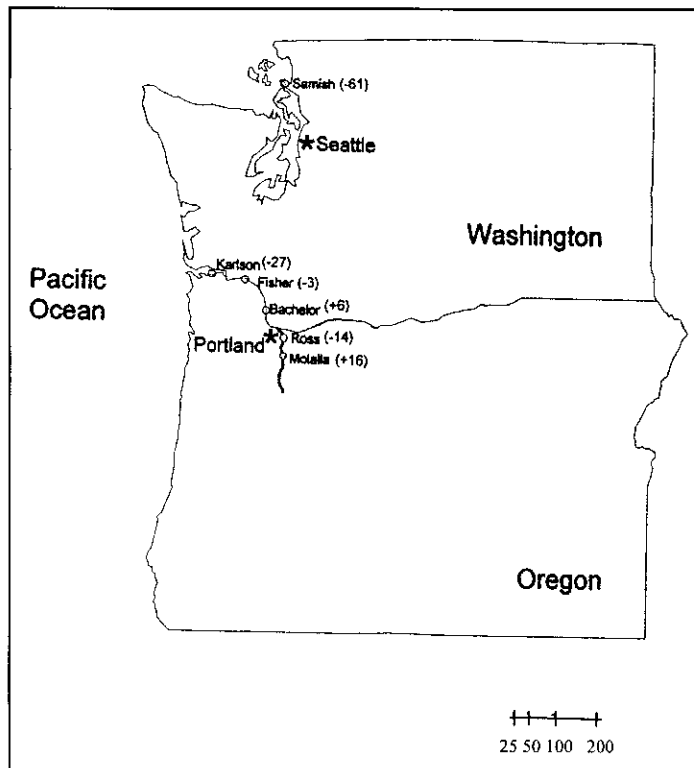


Figure 1. Great blue heron colony locations and distances from nearest pulp and paper mill (in km, + if colony is upstream from mill and - if colony is downstream from mill). 1994-1995.

remaining sites were on or near freshwater. With the exception of the Molalla site, all colonies were in tidal areas. With the exception of Karlson, all colonies were in black cottonwood trees (*Populus trichocarpa*). The Karlson colony was in Sitka spruce (*Picea sitchensis*).

## Methods

### Sampling

We used scan sampling to quantify nest attendance and breeding behaviors of nesting great blue herons from April through mid-July in 1994 and 1995. We controlled for any reaction to observer presence by initiating scans ~ 20 min after our arrival and entry into the blinds. We conducted scans every 10 min and recorded instantaneous observations (Altmann 1974) of adult behavior for every visible nest. Initially, ~ 30 nests in cottonwood colonies were observed during each scan. As the nesting season progressed, fewer nests were

visible because of leaf cover. Consequently, we observed ~ 20 nests from weeks 5-9. Approximately 30 to 35 nests were visible at Karlson throughout the nesting season.

We also recorded information on weather and the presence of predators. Although other potential nest predators (such as red tail hawks [*Buteo jamaicensis*] and ravens [*Corvus corax*]) were observed at all colonies, the only predation attempts observed were on juvenile herons by bald eagles in Samish. Temperature and precipitation were recorded every hour or when conditions changed. Predator data included the time of appearance and departure, reactions of the herons to predators, and activity of the predator. We rated reactions of the herons as 0 (no reaction); 1 (alert behavior, including grunting); 2 (adults left nest but remained nearby); 3 (local flush—adults flew from nests only in the vicinity of the predator); 4 (colony flush). This scoring system allowed us to account for the variation in adult reaction resulting from

different levels of threat posed by different species. Activity categories for predators included flying through the colony, landing in the colony, or predation attempts.

Observation sessions lasted 4-5 hr. We used 40-60x spotting scopes, and observations were conducted from ground blinds or tree stands, depending on nest visibility at the site. Approximate distances between observers and nests ranged from 10-25 m. With the exception of Molalla, all study sites were tidally influenced. Because one of our sites was inaccessible at low tide, we visited all sites during high tide. Observation sessions were centered on high tide such that a 4 hr session would begin 2 hr before high tide. To determine when to initiate observations in Molalla, we extrapolated from the nearest location downstream on the Willamette River that was tidally influenced. All observations were diurnal and were conducted between 0615 and 2015 hr. We visited each colony approximately three times a month from April through July of 1994 and 1995 until the chicks were 9 wk old, for 74-78 hr of observation at each site. The order in which colonies were visited was randomly selected each week.

#### Statistical Analyses

We synchronized nesting chronologies at all sites by defining week 0 as the estimated peak of hatch. For the analysis of nest attendance, we grouped data into present or absent categories. Situations in which one or both adults were present at or near (within 1 m) the nest were included.

We developed a logistic regression model to test for among-site differences in parental nest attendance. We fit a main-effects model that included covariates identified as significant ( $P \leq 0.05$ ) in a drop-of-deviance test (Ramsey and Schaffer 1997). Covariates included temperature, predator presence, time of day, week, and year. Precipitation was a significant explanatory variable for breeding behaviors but not for nest attendance. Because time (week) was a significant covariate, we then analyzed each week separately to determine when significant among-site differences were occurring. We used the Bayes Information Criteria to determine the best interaction model because it emphasizes parsimony of parameters by penalizing larger models (Ramsey and Schaffer 1997). Interactions between site and week, site and year, and temperature and week

were tested. All odds ratios were calculated using Samish as the reference for comparison. We transformed the attendance odds ratios using the natural log to normalize the data, and used simple linear regression to test for relationships between odds ratios and contaminant concentrations.

We counted the number of landing calls by visit, adjusted the total for each site by colony size, and used a square-root transformation to normalize the distribution. Due to small degrees of freedom (six study sites), site comparisons were restricted to paired comparisons of reference versus non-reference sites. We calculated Wilks' lambda and used the Bartlett's approximation to derive  $\chi^2$  (Mardia et al. 1979) to determine whether there was an overall difference in nest exchange rates between reference and non-reference sites. We developed multivariate models to determine whether the number of nest visits was related to year and site effects after accounting for weather and predator effects. We then developed separate multiple linear regressions for each week to examine when the counts were significantly different between reference and non-reference sites. We report significant results using  $P = 0.05$ .

## Results

### General Trends

During both 1994 and 1995, nesting chronology varied by ~2 wk within the six colonies studied. Herons in colonies at Bachelor, Fisher, Molalla, and Ross generally initiated incubation in mid-March. Estimated peak of hatch for these colonies was in mid-April. In contrast, colonies at Karlson and Samish generally initiated incubation in the end of March/beginning of April; estimated peak of hatch for these two colonies was in early May. The estimated peak of fledge followed a similar pattern, with juvenile herons from Bachelor, Fisher, Molalla, and Ross fledging in early to mid-June, while Karlson and Samish fledged the maximum number of young in late June to early July. The timing of incubation and peak of hatch was consistent between years, whereas the peak of fledge was earlier by at least one week in 1995 for all colonies except Samish.

During both 1994 and 1995, colonies at Bachelor, Fisher, Karlson, and Samish were adjacent to active bald eagle nests. We observed bald eagle intrusions in the Fisher, Karlson, and Samish colo-

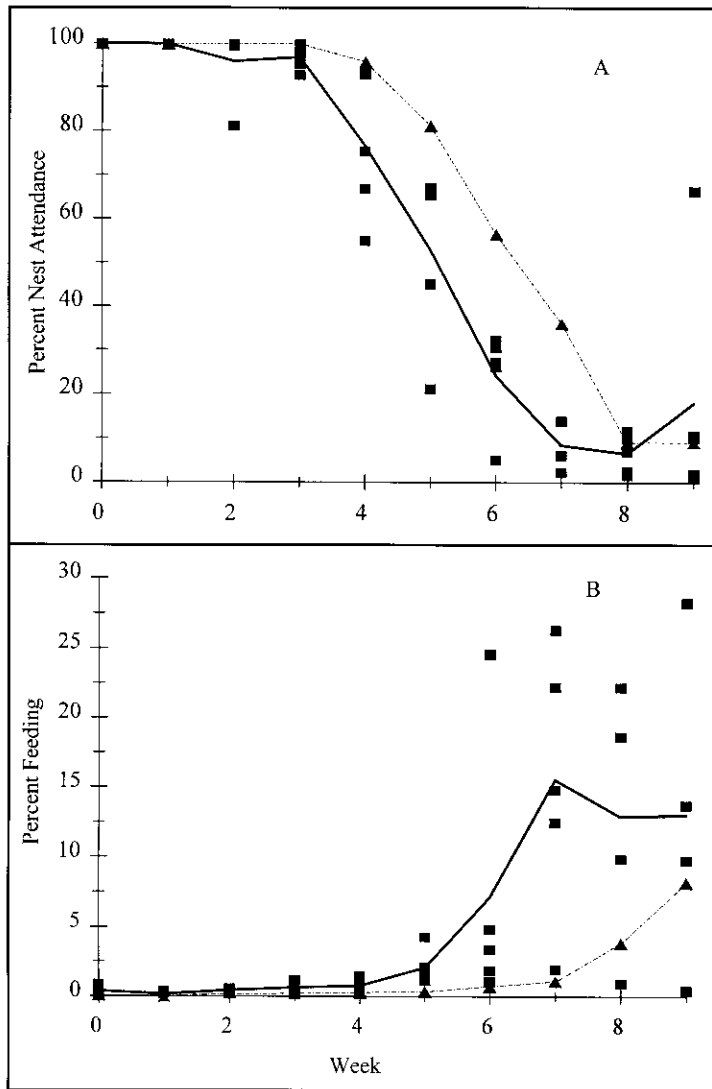


Figure 2. Percent of adult herons in attendance (A) and feeding (B) in six western Oregon and Washington colonies each week, 1994-1995. Triangles and broken line represent reference site, squares and solid line represent non-reference sites.

nies. We observed one successful predation event by a bald eagle in Samish, in which the bald eagle flew out of sight with a 3-4 wk-old heron while the adults were not attending the nest.

The rate of nest visits changed greatly with time over the breeding season. The percentage of adults present at a nest followed a sigmoid curve (Figure 2A). One or both adults were continuously present at most nests during weeks 0-3, then adult attendance declined rapidly, and few adults

were present at their nests during the last 2 wk of the nesting period. Throughout the nesting cycle, adults at Samish were present at their nests more than at other sites. The percentage of adults feeding chicks increased after week 4 (Figure 2B).

#### Contaminants

Contaminant data from 1994 and 1995 were not significantly different for *p,p'*-DDE, total PCBs, or 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD),

TABLE 1. Organochlorine concentrations (fresh wet weight) in great blue heron eggs (N=10) from the Columbia and Willamette rivers and Puget Sound, 1994-95. Data are adapted from Thomas and Anthony (1999). Results are geometric means and (95% confidence intervals). Results for DDE and PCB are reported in ng/g. TCDD results are reported in pg/g. Means with identical superscripts are not significantly different.

	Bachelor	Fisher	Karlson	Molalla	Ross	Samish
p,p'-DDE	331 <sup>a</sup> (190-575)	393 <sup>a</sup> (196-788)	852 <sup>a</sup> (657-1105)	520 <sup>a</sup> (269-1005)	1432 <sup>b</sup> (554-3703)	121 <sup>a</sup> (81-182)
Total	480 <sup>a</sup> (308-747)	744 <sup>ab</sup> (403-1377)	1574 <sup>ab</sup> (1158-2132)	474 <sup>a</sup> (310-726)	2842 <sup>b</sup> (1120-7214)	292 <sup>a</sup> (194-438)
2,3,7,8-TCDD	2.57 (1.68-3.93)	2.94 (1.52-5.69)	7.42 (5.12-10.76)	3.10 (2.50-3.85)	5.08 (2.31-11.19)	2.44 (1.42-4.20)

so data from the 2 years were pooled. Significant among-site differences were present in concentrations of p,p'-DDE ( $P < 0.001$ ), total PCBs ( $P = 0.01$ ) and TCDD ( $P = 0.03$ ). Eggs from Ross Island contained the highest concentrations of both DDE and total PCBs; eggs from Karlson Island contained the most TCDD (Table 1).

#### Nest Attendance

Location was a significant explanatory variable ( $P < 0.005$ ) for differences in nest attendance after accounting for differences in year, week, time of day, temperature, and presence of predators as covariates. Week ( $P < 0.001$ ), temperature ( $P < 0.001$ ), and time of day ( $P < 0.001$ ) were also significant explanatory variables; the remaining variables were included in the model to account for known sources of variability.

The overall odds ratio (the likelihood of an event occurring) of at least one adult heron being present at the nest was significantly ( $P < 0.05$ ) lower for all non-reference sites compared to Samish (Table 2). Patterns of adult nest attendance were most similar between Fisher and Samish. The odds ratio for adult presence was lowest for

Ross and was 0.05 times the odds of adults being present at Samish. The log of odds ratios for adult nest attendance were negatively correlated with DDE ( $r = -0.78$ ,  $P = 0.01$ ) and PCB ( $r = -0.64$ ,  $P = 0.04$ ) concentrations (Figures 3 and 4), but not with TCDD concentrations. PCB and DDE concentrations in eggs were collinear ( $P = 0.001$ ).

There were significant interactions between the year, week, and site effects on the probability of nest attendance by adult herons (Table 2). Compared to Samish, the odds ratio for at least one adult being present at its nest was greater in 1994 for the Fisher and Karlson colonies. For Bachelor, Molalla, and Ross colonies, the odds of adults being present were greater in 1995 relative to Samish. Significant interactions were detected between site and week relative to Samish. At Bachelor, Fisher, Molalla, and Ross, the odds ratios for adult nest attendance increased with successive weeks, compared to Samish. With the exception of Karlson, adults at non-reference sites appeared to be present later in the season. The odds of Karlson adults being present at the nest relative to Samish decreased with successive weeks. The temperature-by-week interaction was not significant for any model.

TABLE 2. Odds ratios and (95% confidence intervals) for main effects and interaction terms for great blue heron nesting behaviors (N = 2084). Columbia and Willamette rivers, 1994-1995. All odds ratios were calculated relative to Samish, the reference site. All odds ratios are significant at  $P \leq 0.05$ .

Model	Bachelor	Fisher	Karlson	Molalla	Ross
Main effect	0.38 (0.34-0.41)	0.51 (0.46-0.56)	0.40 (0.37-0.44)	0.25 (0.22-0.27)	0.05 (0.04-0.06)
Interactions					
Site x Week	1.32 (1.24-1.41)	1.23 (1.15-1.31)	0.83 (0.77-0.90)	1.30 (1.22-1.39)	1.48 (1.37-1.60)
Site x Year	0.55 (0.45-0.67)	2.62 (2.16-3.18)	1.77 (1.44-2.17)	0.78 (0.64-0.96)	0.16 (0.13-0.20)

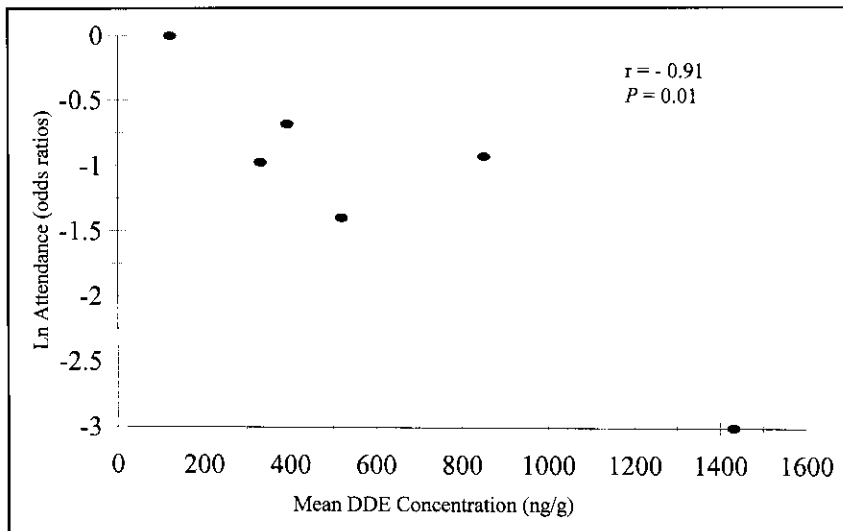


Figure 3. Negative correlation between natural log-transformed odds ratios for adult nest attendance and DDE concentrations (site means in ng/g wet weight) in great blue heron eggs from the Columbia and Willamette rivers and Puget Sound, 1994-1995.

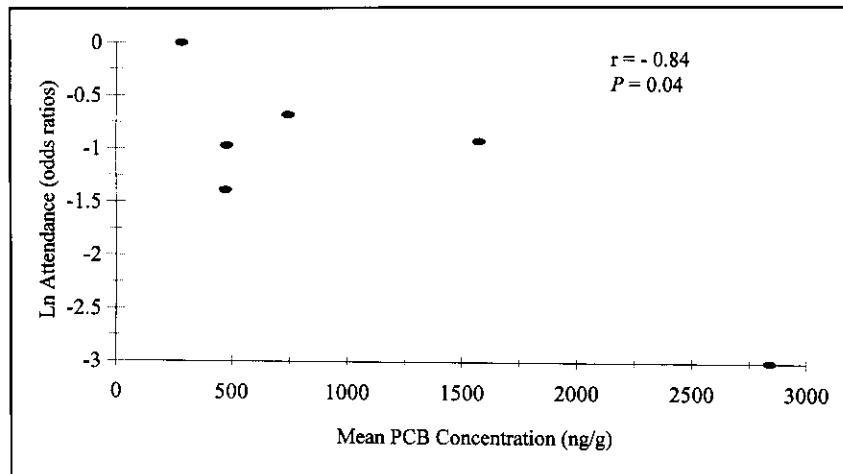


Figure 4. Negative correlation between natural log-transformed odds ratios for adult nest attendance and PCB concentrations (site means in ng/g wet weight) in great blue heron eggs from the Columbia and Willamette rivers and Puget Sound, 1994-1995.

### Nest Visits

The rate of nest visits peaked at week 2 and gradually declined to week 9 (Figure 5). After accounting for the effects of temperature, precipitation, predator presence, week, and year as covariates, rates of nest visitation at Samish differed significantly from all other sites ( $P < 0.001$ ). Rates of nest visits at Samish were greater relative to non-reference sites during weeks 0-2. No difference was

detected in visitation rates between Samish and non-reference sites during weeks 3-9.

### Discussion

Patterns of parental nest attendance and nest visitation were different among sites. Nest attendance was inversely related to DDE and PCB concentrations in eggs. However, the reproductive output of all six colonies was similar to that reported

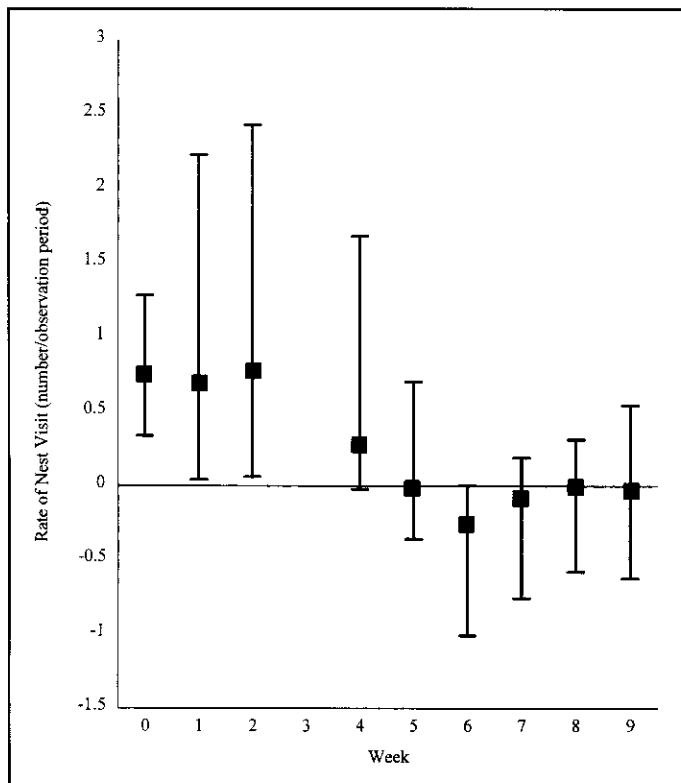


Figure 5. Parameter estimates and 95% confidence intervals for rate of nest visitation over time at reference site relative to non-reference sites for six great blue heron colonies, Columbia and Willamette rivers and Puget Sound, 1994-1995. Total number of nest visits were summed by observation period and adjusted for colony size.

for healthy populations of great blue herons (McAloney 1973, Blus et al. 1980, Dowd and Flake 1984, Fitzner et al. 1988). The differences we observed in nest attendance and rate of nest visits did not affect hatching success or nestling survival up to fledging.

The nest attendance patterns that we observed were similar to other studies of great blue herons in California (Pratt 1970) and South Dakota (Dowd and Flake 1984). In all three studies, adults displayed nearly constant nest attendance during weeks 2-3 posthatch, with attentiveness dropping sharply after week 4. McAloney (1973) reported nearly continuous brooding of chicks for the first 2 wk posthatch.

The percentage of adults observed feeding juveniles while at their nests increased during the last third of the nesting cycle. Because feeding

sessions were brief and were infrequently observed, the rate of nest visitation provides a better indication of feeding frequencies at each site. The feeding frequencies presented here are slight overestimates because every nest visit did not result in feeding of the young.

The pattern that we observed in nest visits agreed with previous studies, which suggested that younger chicks are fed more often (Pratt 1970, Dowd and Flake 1984). The highest rate of nest visitation in this study occurred during week 2 posthatch, which was 2 wk earlier than peaks reported for herons nesting in British Columbia (Butler 1992) and South Dakota (Dowd and Flake 1984). Energy demands of captive great blue herons are greatest between weeks 4-6 (Butler 1993), which has important implications for chicks in our study areas. If the feeding pattern of the adults

does not match the growth pattern of the chicks, chicks may grow more slowly or have insufficient lipid reserves at fledging. Prey capture rates of juvenile herons are roughly half that of adults during the 2 mo following fledging (Quinney and Smith 1980), so that lipid reserves are crucial for survival during this period.

There were large differences in bald eagle presence among the sites. During 1994-95, active bald eagle nests were adjacent to the heron colonies on Bachelor, Fisher, Karlson, and Samish islands. Eagles were observed in the Samish colony during 14 out of 18 visits, for a total of 8.4% (370 of 4,424 min) of our observation time. Bald eagles were observed during 2 out of 18 visits for a total of 0.4% (18 out of 4,568 min) of our observation time at Fisher, and during 3 out of 18 visits (4 out of 4,570 min or 0.09%) to Karlson. Eagle intrusions were not observed at the Bachelor, Molalla, or Ross Island colonies. Adult great blue herons reacted strongly to the presence of bald eagles with alarm calls and increased vigilance behaviors. However, increased vigilance of Samish adults from frequent presence of bald eagles was not sufficient to explain among-site differences in nesting behaviors. Behavioral differences among sites were still significant after accounting for the presence of predators.

In previous studies, alterations in patterns of nest attendance, feeding, and incubation have most commonly been associated with environmental contaminants. In laboratory studies using ring doves (*Streptopelia risoria*), significant alterations in the amount of time involved in courtship activity were observed in birds fed elevated concentrations of DDE relative to control birds (Haegle and Hudson 1973, 1977). Altered courtship behavior, reduced nest attendance, and increased length of breeding cycle have also been observed in ring doves dosed with combinations of DDE and PCB (McArthur et al. 1983). In high-dose doves, effects also included prolonged incubation period, reduced brooding and feeding, and decreased fledge success.

Similar trends have been observed in field studies. Altered incubation behavior and altered minimum flushing distance were observed in herring gulls (*Larus argentatus*) exposed to elevated levels of DDT and DDE (Keith 1966, Fox et al. 1978). Increased length of incubation and increased nest abandonment were observed in Forster's terns

exposed to OC compounds including dioxins, furans, and PCB (Kubiak et al. 1989). Reduced nest defense in prairie falcons (*Falco mexicanus*) and merlins was associated with elevated concentrations of DDE and possibly PCB (Fyfe et al. 1976).

The TCDD and PCB concentrations observed during this study (2.4 to 7.4 pg/g, and 0.29 to 2.8 pg/g) were lower than those observed in Kubiak et al. (1989), and may be below the threshold that adversely affects survival through altered adult behavior. DDE concentrations (0.12 to 1.4 pg/g) in our study, however, were similar to levels observed to cause abnormal nesting behavior in herring gulls and prairie falcons (Keith 1966, Fyfe et al. 1976).

Differences in nest attendance among sites were correlated with DDE and PCB concentrations in eggs. Eggs from Ross Island had the highest concentrations of DDE and PCB; these adults spent the least amount of time at their nests. In contrast, eggs from Samish contained the lowest concentrations of all three organochlorine contaminants, and adults spent the greatest amount of time at their nests. Adults at Samish also maintained higher rates of nest visitation, relative to all other sites, during the first 4 wk after the peak of hatch. These results suggest that contaminants affected nest attendance and prey delivery of herons in this study.

Although we suggest that contaminants had an effect on breeding behavior of great blue herons, other factors could have been responsible for differences in behavior among the colonies. Prey size and availability could have differed among the colonies and may be responsible for the among-site differences we observed in adult nest attendance. Prey may be more available at Samish relative to the rest of the sites. Herons typically feed in water less than 60 cm deep (Butler 1992), and Samish Island was adjacent to extensive eelgrass mudflats that may provide optimal foraging habitat at low tide. Typical feeding areas of herons on the Columbia and Willamette rivers include backwater sloughs that are frequently steep-sided, thus providing smaller areas of suitable habitat nearby. The distance to foraging areas was short and similar for all colonies.

Herons may also be selecting prey of different sizes at Samish compared to the non-reference sites. Herons at Samish appeared to make a

greater number of short trips to foraging areas, resulting in a higher rate of nest visitation, and allowing greater nest attendance relative to other sites. In contrast, herons on the Columbia and Willamette rivers may make fewer, longer trips to foraging areas, resulting in lower rates of nest visitation. According to the optimal foraging theory (Schoener 1969), predators that pursue their prey over greater distances should take larger prey to maximize net energy intake. For a unit increase in the distance between predator and prey, the change in handling time (amount of energy spent capturing prey per unit energy derived from prey per unit time) is larger for smaller prey. Consequently, for larger foraging distances, the minimum prey size must be larger for predators to maintain a positive energy balance. Only large prey should be taken at great distances, but the largest prey taken at a given distance may be smaller than the largest taken at smaller distances. Thus, the chicks at Samish may be fed more frequently with prey items of a smaller average size relative to non-reference sites. Chicks at the non-reference sites may be fed prey items of a larger average size less frequently. Although the prey we collected for contaminant analyses did appear to be smaller than prey collected from non-reference sites, we did not collect data on individual

prey size and are unable to test that aspect of our theory. These factors should be considered when interpreting our results, and in future studies.

Although colonies exhibited healthy rates of hatch, fledge, and reproductive success, patterns of adult nest attendance were different among sites. The differences we observed in nesting behavior and residue levels did not affect survival of juvenile herons up to fledging. However, additional study is needed to determine the effect of current contaminant loads on juvenile fledging success.

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### Literature Cited

- Altmann, J. 1974. Observational study of behavior: sampling methods. *Behavior* 49:227-267.
- Anthony, R. G., M. G. Garrett, and C. Schuler. 1993. Environmental contaminants in bald eagles in the Columbia River Estuary. *Journal of Wildlife Management* 57:10-19.
- Blus, L. J., C. J. Henny, and T. E. Kaiser. 1980. Pollution ecology of breeding great blue herons in the Columbia Basin, Oregon and Washington. *Murrelet* 61:63-71.
- Butler, R. W. 1992. Great Blue Heron. Pages 1-20 *In* A. Poole, P. Stettenheim and F. Gill (editors), *The Birds of North America*, no. 25. Academy of Natural Sciences: Washington, D.C.
- Butler, R. W. 1993. Time of breeding in relation to food availability of female great blue herons (*Ardea herodias*). *Auk* 110:693-701.
- Cobb, G. P., D. M. Norman, and R. J. Kendall. 1994. Organochlorine contaminant assessment in great blue herons using traditional and nonlethal monitoring techniques. *Environmental Pollution* 83:299-309.
- Curtis, L. R., H. M. Carpenter, R.M. Donohoe, D.E. Williams, O.R. Hodstrom, M.L. Deinzer, M.A. Bellstein, E. Foster, and R. Gates. 1993. Sensitivity of cytochrome P450-1A1 induction in fish as a biomarker for distribution of TCDD and TCDF in the Willamette River, Oregon. *Environmental Science and Technology* 27:2149-2157.
- Dowd, E. M., and L. D. Flake. 1984. Great blue heron nesting biology on the James River in South Dakota. *Prairie Naturalist* 16:159-166.
- Elliot, J. E., R. W. Butler, R. J. Norstrom, and P. E. Whitehead. 1989. Environmental contaminants and reproductive success of great blue herons *Ardea herodias* in British Columbia, 1986-87. *Environmental Pollution* 59:91-114.
- Fitzner, R. E., L. J. Blus, C.J. Henny, and D.W. Carlile. 1988. Organochlorine residues in great blue herons in the northwestern United States. *Colonial Waterbirds* 11:293-300.
- Fox, G. A., A. P. Gilman, D. B. Peakall, and F. W. Anderka. 1978. Behavioral abnormalities of nesting Lake Ontario herring gulls. *Journal of Wildlife Management* 42:477-483.
- Franklin, J. F., and C. T. Dyrness. 1988. *Natural vegetation of Oregon and Washington*. Oregon State University Press, Corvallis, Oregon.
- Fyfe, R. W., R. W. Risebrough, and W. Walker II. 1976. Pollutant effects on the reproduction of the prairie falcons and merlins of the Canadian prairies. *Canadian Field-Naturalist* 90:346-355.
- Gill, F. B. 1990. *Ornithology*. Freeman, New York.

- Haegel, M. A., and R. H. Hudson. 1973. DDE effects on reproduction of ring doves. *Environmental Pollution* 4: 53-57.
- Haegel, M. A., and R. H. Hudson. 1977. Reduction of courtship behavior induced by DDE in male ringed turtle doves. *Wilson Bulletin* 89:593-601.
- Henny, C. J., L. J. Blus, S. V. Gregory, and C. J. Stafford. 1981. Pages 1763-1780 *In* J. A. Chapman and D. Pursely (editors), PCBs and organochlorine pesticides in wild mink and river otters from Oregon. *Worldwide Furbearer Conference Proceedings*, Aug 3-11, 1980. Frostburg, Maryland.
- Henny, C. J., L. J. Blus, A. J. Krynitsky, and C. M. Bunck. 1984. Current impact of DDE on black-crowned night herons in the intermountain west. *Journal of Wildlife Management* 48:1-13.
- Henny, C. J., R. A. Grove, and O. R. Hedstrom. 1996. A field evaluation of mink and river otter on the Lower Columbia River and the influence of environmental contaminants. Final Report for the Lower Columbia River Bi-State Water Quality Program. National Biological Service, Northwest Research Station, Corvallis, Oregon.
- Keith, J. A. 1966. Reproduction in a population of herring gulls (*Larus argentatus*) contaminated by DDT. *Journal of Applied Ecology* 3 (Supplement): 57-70.
- Kubiak, T. J., H. J. Harris, L. M. Smith, T. R. Smith, T. R. Schwartz, D. L. Stalling, J. A. Trick, L. Sileo, D. E. Docherty, and T. C. Erdman. 1989. Microcontaminants and reproductive impairment of the Forster's tern on Green Bay, Lake Michigan—1983. *Archives of Environmental Contaminants and Toxicology* 18:706-727.
- Mardia, K. V., J. T. Kent, and J. M. Bibby. 1979. *Multivariate Analysis*. Academic Press, New York.
- McAloney, K. 1973. The breeding biology of the great blue heron on Tobacco Island, Nova Scotia. *Canadian Field-Naturalist* 87:137-140.
- McArthur, M. B., G. A. Fox, D. B. Peakall, and B. R. Philogene. 1983. Ecological significance of behavioral and hormonal abnormalities in breeding ring doves fed an organochlorine chemical mixture. *Archives of Environmental Contaminants and Toxicology* 12:343-353.
- Parsons, A. H., S. L. Huntley, E. S. Ebert, E. R. Algeo, and R. E. Keenan. 1991. Risk assessment for dioxin in Columbia River fish. *Chemosphere* 23:1709-1717.
- Peakall, D. B., and M. L. Peakall. 1973. Effect of polychlorinated biphenyl on the reproduction of artificially and naturally incubated dove eggs. *Journal of Applied Ecology* 10:863-868.
- Platonow, N.S., and L.H. Karstad. 1973. Dietary effects of polychlorinated biphenyls on mink. *Canadian Journal of Comparative Medicine* 37:376-398.
- Pratt, H. M. 1970. Breeding biology of great blue herons and common egrets in central California. *Condor* 72:407-416.
- Quinney, T. E., and P. C. Smith. 1980. Comparative foraging behavior and efficiency of adult and juvenile great blue herons. *Canadian Journal of Zoology* 58:168-1173.
- Ramsey, F. L., and D. W. Schaffer. 1997. *Statistical Sleuth: A Course in Methods of Data Analysis*. Duxbury Press, Belmont, California.
- Schmitt, C. J., J. L. Zajicek, J. L. and P.H. Peterman. 1990. National contaminant biomonitoring program: residue of organochlorine chemicals in freshwater fish, 1976-1984. *Archives of Environmental Contaminants and Toxicology* 19:748-781.
- Schoener, T. W. 1969. Models of optimal size for solitary predators. *American Naturalist* 103:277-313.
- Thomas, C. M., and R. G. Anthony. 1999. Environmental contaminants in great blue herons (*Ardea herodias*) from the lower Columbia and Willamette Rivers, Oregon and Washington, USA. *Environmental Toxicology and Chemistry* 18:2804-2816.
- U.S. Environmental Protection Agency. 1992. National study of chemical residues in fish. Office of Science and Technology, Washington, D.C. 2 Volumes. (EPA 823-R-92-008a and EPA 823-R-92-008b).
- U.S. Fish and Wildlife Service. 1999. Organochlorine contaminants in double-crested cormorants from Lewis and Clark National Wildlife Refuge in the Columbia River Estuary. Unpublished report on file at Oregon Fish and Wildlife Office, Portland, Oregon.
- Whitehead, P. E. 1990. Toxic chemicals in great blue heron (*Ardea herodias*) eggs in the Strait of Georgia. Pages 177-183 *In* K. Vermeer and R.W. Butler (editors), *The status and ecology of marine and shoreline birds in the Strait of Georgia*, B.C. Canadian Wildlife Service, Ottawa.

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