

ABSTRACT

Title of Thesis: THE ROLE OF CONTAMINANT EXPOSURE AND HABITAT SUITABILITY IN NEST SITE USE AND PRODUCTIVITY OF OSPREYS (*PANDION HALIAETUS*) BREEDING ON THE DELAWARE RIVER AND BAY

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In 2002, contaminant exposure, reproduction, and habitat use of ospreys along 3 segments of a 300-km stretch of the Delaware Bay area, and a reference area were evaluated. Fresh eggs were collected and analyzed for contaminants; fate of nests was monitored through fledging. Concentrations of *p,p'*-DDE and PCBs in eggs collected between the C&D Canal and Trenton resembled elevated levels found in the Chesapeake Bay. Productivity for Inland Bays and southern Delaware Bay was 1.17 and 1.42 young fledged/active nest; north of the C&D Canal productivity averaged 1 fledgling/active nest. An examination of osprey habitat use showed that presence of active nests was associated with water depth and clarity, distance to active osprey nests, and presence of urban land, while hatching success was associated with organic contaminants in eggs. Contaminants continue to be a significant stressor on osprey productivity, particularly in the northern Delaware Bay area.

THE ROLE OF CONTAMINANT EXPOSURE AND HABITAT SUITABILITY IN
NEST SITE USE AND PRODUCTIVITY OF OSPREYS (*PANDION HALIAETUS*)
BREEDING ON THE DELAWARE RIVER AND BAY

by

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CHAPTER 1: INTRODUCTION

Individual organisms have specific habitat requirements that vary among species and temporally within species, depending on their life stage and breeding status (Anderson 2000). It has long been recognized that quality and availability of habitat are important considerations for managers intending to increase wildlife populations (Anderson 2000). Many stressors, including environmental contaminants and pollution, have been demonstrated to adversely affect wildlife populations and their habitat. Some of the major challenges in assessment of such risks for wildlife are the integration of multiple stressors and the evaluation of risk over a large scale (SETAC 1997). Landscape scale habitat evaluations that integrate human impacts with other environmental variables affecting ecosystems are necessary for effective management decision-making (Anderson 2000).

As reviewed in Hoffman et al. (1990), the first records of wildlife affected by contaminants occurred during the industrial revolution but persistent organic contaminants became a concern following the development of pesticides during World War II. In the mid to late twentieth century, effects of organochlorine, carbamate, and organophosphorus pesticides on wildlife were becoming apparent. This led to the development of toxicity screening for pesticides and extensive field studies of contaminant exposure and effects on wildlife. Wildlife die-offs, malformed birds, and reproductive failures have been attributed to organochlorine, organophosphate, and carbamate pesticides in areas throughout the United States. Probably the worst case-scenario of direct contaminant effects was realized with dichlorodiphenyltrichloroethane (DDT), which nearly led to the extinction of several avian species (Hoffman et al. 2003).

It has long been recognized that a multi-disciplinary approach to wildlife toxicology, chemical screening in the laboratory, ecological field studies, and controlled field experiments are the most effective ways to address these complex problems (Hoffman et al. 1990). Nonetheless, effects of synergism and additivity of pesticides on wildlife have yet to be evaluated fully, and effects of multiple habitat factors need to be considered for better evaluation of population level effects (Hoffman et al. 1990). Currently ecotoxicological research encompasses exposure and effects evaluations of pesticides, petroleum and polycyclic aromatic hydrocarbons, metals, trace elements, nuclear and thermal waste, urban runoff, pathogens, byproducts of mining and smelting, spent munitions, genotoxic and endocrine disruptive chemicals, and the cocktail of anthropogenic compounds in sewage outflow, among other things (Hoffman et al. 2003).

Of ecotoxicological research conducted on terrestrial vertebrates in estuaries along the Atlantic Coast of the U.S., the majority was conducted in the 1970s, indicating a decreasing priority of toxicology in biological research (Rattner et al. 2000). However, this does not necessarily reflect a decreasing need for ecotoxicological research: analyses in wildlife have been conducted for only 118 of the more than 75,000 chemicals in commerce in the U.S. (Rattner et al. 2000). Most of the existing contaminant data are for waterfowl, though a significant amount of research has been conducted on raptors, songbirds, and other waterbirds (Rattner et al. 2000). The focus of contaminant research on die-offs and known contaminated areas has left data gaps, and a paucity of spatially and temporally consistent data (Rattner et al. 2000). Several large National Wildlife Refuges and National Parks along the Atlantic Coast have no information on contaminant exposure on their lands, and many more do not have data from the past decade (Rattner at

al. 2000; Cohen et al. 2003). The middle Delaware River watershed had no terrestrial vertebrate contaminant exposure data between 1990 and 2000, and was one of two Atlantic Coast watersheds with both water quality problems and a high vulnerability to pollution (Cohen et al. 2003). Prior to 2000, the Delaware Inland Bays watershed had no records of contaminants in wildlife (Rattner et al. 2000). In addition to the spatial data gaps, limited data are available for classes of compounds that have potential to cause great harm.

Avian species, in particular waterbirds, are excellent monitors of environmental contamination (Furness and Greenwood 1993; Kushlan 1993; Golden and Rattner 2003). To obtain realistic estimates of bioavailability of contaminants in the environment, it is appropriate to examine concentrations in wildlife that occupy a high trophic level (Golden and Rattner 2003). Species are selected for monitoring for various reasons, including presence of the species in an area of interest, sensitivity to the contaminant of interest, or ecosystem function of the species and their relationship to the contaminated medium (Golden and Rattner 2003). In a ranking of 25 potential sentinel species for utility in biomonitoring and vulnerability to contaminants, the osprey ranked high in terms of both utility and vulnerability for evaluation of persistent organic pollutants and mercury (Golden and Rattner 2003). The species that ranked above the osprey on these scales do not occur in the Delaware Bay in great enough abundance or over a broad enough range to be useful for evaluating this region, making the osprey the best selection for this large study area. The osprey exhibits several characteristics that make it an extremely useful sentinel of environmental contamination for aquatic environments: worldwide distribution, allowing for consistent methodology and inter-site comparisons;

sensitivity to pollutants; dependence on fish for most food, exposing them to contaminants that bioaccumulate and biomagnify; concentrations of contaminants are found in eggs, nestling blood, and nestling feathers, and hence can be used to indicate local pollution; nests are generally built on accessible structures, including man-made platforms and channel markers; and ospreys tolerate short-term disturbance and removal of a sample egg (Poole 1989; Henny and Wight 1969; Henny 1983).

The purpose of the present study was to (1) evaluate contaminant exposure of ospreys nesting in the Delaware River and Bay, (2) monitor osprey productivity as an integrator of multiple stressors, (3) to evaluate the relative importance of contaminant exposure of ospreys nesting in the Delaware River and Bay to other habitat variables, (4) identify gradients in contaminants in osprey eggs and compare them to those seen in water and sediment, (5) to compare the concentration of contaminants in osprey eggs in this region to values in other areas of the United States, (6) to explain the difference in osprey nest density between northern and southern Delaware River and Bay by producing a habitat suitability model for estuarine breeding ospreys based on field data, (7) to evaluate existing habitat suitability models for osprey and compare them to the model developed from this research, and (8) to provide management recommendations regarding osprey habitat in the Delaware River and Bay.

CHAPTER 2: EVALUATION OF CONTAMINANT EXPOSURE AND EFFECTS

ABSTRACT

Despite serious water quality problems, contaminated sediments, and considerable pollutant loading and retention, Delaware Bay and River provide important habitat for wildlife. In 2002, we conducted a comprehensive evaluation of contaminant exposure and reproduction of ospreys breeding in a coastal reference area (Delaware Inland Bays), and along 3 segments of a 200 km stretch of the Delaware Bay and River (Lewes, DE to C&D Canal; C&D Canal to Trenton, New Jersey; Trenton to East Stroudsburg, Pennsylvania). A sample egg was collected from each of 39 nests (N=12/study segment, N=3 for Trenton to East Stroudsburg) and analyzed for organochlorine pesticides, PCBs, and mercury; a subset of 14 or 15 eggs were analyzed for perfluorinated compounds and polybrominated diphenyl ethers. The fate of eggs remaining in each nest was monitored at weekly intervals through fledging. Concentrations of 10 organochlorine pesticides or metabolites (e.g., p,p'-DDE, dieldrin, heptachlor epoxide, chlordane), total PCBs, and several Ah receptor-active PCB congeners were greater ($p < 0.05$) in eggs collected from the C&D Canal to Trenton study segment compared to other sites. Concentrations of p,p'-DDE (0.785-3.84 $\mu\text{g/g ww}$) and total PCBs (5.50-14.5 $\mu\text{g/g ww}$) in eggs collected between the C&D Canal and Trenton were not unlike elevated levels recently found in the Chesapeake Bay regions of concern. The ratio of Aroclor 1254 to Aroclor 1260 was consistent among all sites, suggesting a common source of PCBs. In all study segments, at least 1 young was fledged from 66-75% of the nests. Average productivity for Delaware Inland Bays and southern Delaware Bay was 1.17 and 1.42 fledglings per active nest; north of the C&D Canal productivity averaged 1 fledgling per active nest,

which is marginally adequate to maintain the population. These findings indicate environmental contaminants continue to be a significant stressor on osprey productivity in the northern Delaware Bay and River.

INTRODUCTION

The Delaware River and Bay provide important habitat for a diversity of wildlife, including ospreys. Delaware Bay is part of the National Estuary Program, the Western Hemisphere Shorebird Reserve Network, on the “Last Great Place” list of The Nature Conservancy, and a Wetland of International Significance (Dove and Nyman 1995). The Delaware River is the largest un-dammed river in the eastern United States; it drains over 30,000 square km of land and provides water for more than 17 million people (Kausch et al. 2000). The coastal zone between the Chesapeake & Delaware (C&D) canal and the southern border of Delaware is characterized by poorly drained mineral and organic soils and extensive tidal marshlands, while north of the canal soils are more well drained and tidal wetlands are limited to the near shore area (Hess et al. 2000). A more extensive review of the habitat in Delaware can be found in Hess et al. 2000.

The coastal zone in Delaware is highly industrialized, with factories producing steel (Citi Steel), manufacturing industrial and commercial chemicals and plastics (DuPont, General Chemical, ICI Americas, Oxychem, Standard Chlorine, Kaneka Delaware Corporation, Formosa Plastics) and refining petroleum (Motiva). Over 50 Superfund sites in Pennsylvania are located within the Delaware River watershed, and an additional 41 Superfund sites are located within Delaware. The Delaware Bay is the largest oil transfer port of entry on the east coast, and agricultural lands and intensive poultry farming surround it. In addition to industrial and agricultural stressors, the

Delaware Bay has more than twice the population density and percent of land in urban land use than the nearby Chesapeake Bay (Castro and Driscoll 2002).

The Delaware River does not support drinking water use between Camden and Trenton, New Jersey, because of high levels of 1,2-dichloroethane and tetrachloroethene (chemicals used for industrial processes and dry cleaning). New Jersey releases more 1,2-dichloroethane into water than any other state (USEPA 2002). Between Trenton, New Jersey, and Wilmington, Delaware, fluctuations in pH and dissolved oxygen do not always support aquatic life, and declining fish populations are a cause for concern. Concentrations of DDT, dieldrin, chlordane, PCBs, dioxins, polynuclear aromatic hydrocarbons, As, Cr, Cu, Hg, Pb, and Zn in the Delaware River and Bay exceed sediment contamination thresholds and water quality criteria.

A sediment contaminants study, utilizing the human reporter gene system (HRGS) bioassay, an indicator of exposure to PAHs or chlorinated hydrocarbons, suggested that the northern Bay and southern River are degraded due to contamination, and that the degradation follows a north to south gradient (McCoy et al. 2002). The HRGS bioassay of P450 showed the greatest response with sediment collected directly across from the Philadelphia airport, compared to areas south of the airport in the Delaware River and Bay (McCoy et al. 2002). PAHs are the most abundant contaminant in marine sediments found in areas such as the Delaware Bay (McCoy et al. 2002). Sediments collected from marshes near Dover, Delaware, also contained elevated concentrations of dioxins and dibenzofurans (McCoy et al. 2002).

A 10-day static toxicity test with the amphipod *Ampelisca abdita* found high mortality ($\approx 80\%$) in sediment collected from 3 sampling sites in the northern bay area

near Salem Cove, Little Tinicum, and Cherry Island Flats. However, sediments from other sites sampled in close proximity to these sites did not elicit high mortality in this toxicity test (NOAA 2001).

Finfish consumption advisories are in effect north of the C&D Canal to the Delaware-Pennsylvania border and in the Pennsylvania reach of the Delaware River from Yardley, Pennsylvania to Delaware due to high concentrations of contaminants such as DDT, dieldrin, chlordane, PCBs, dioxin, As and Hg (Kausch et al. 2000; Sutton et al. 1996; PAFBC 2001). The number of adult American shad (*Alosa sapidissima*) passing Lambertville, New Jersey and New Hope, Pennsylvania decreased by 25% from 1996 to 1998 and by 94% from 1998 to 1999 for unknown reasons, while the striped bass population increased between 1990 and 2000 (Kausch et al. 2000).

Historically ospreys were common breeders along the Delaware Bay, with over 90 nests observed in Kent County alone in 1942 (Hess et al. 2000). However, this part of the osprey population has not recovered from reproductive problems associated with exposure to DDT and its metabolites, and ospreys are currently listed as uncommon breeders outside of the Inland Bays (Hess et al. 2000). In the late 1980's, eggshell thinning (up to 23% in addled eggs) and reproductive impairment due to *p,p'*-DDE, and to a lesser degree PCBs, were reported in Delaware Bay ospreys (*Pandion halieetus*), peregrine falcons (*Falco peregrinus*), bald eagles (*Haliaeetus leucocephalus*) and great blue herons (*Ardea herodias*; Steidl et al. 1991a, 1991b, 1991c; USFWS 1991, 1995; Wiemeyer et al. 1988, 1993; Parsons and McCoplin 1995). A detailed evaluation of contaminant exposure and productivity in a small sample of ospreys breeding on the

Salem River, New Jersey, indicated eggshell thinning and reduced hatching success were still affecting this population in 1989 (Steidl et al. 1991b).

A small collection of osprey eggs from two Delaware Bay tributaries below the heavily polluted regions in southern New Jersey (5 eggs from the Salem River and 6 eggs from the Maurice River) was conducted in 1998 to reexamine contaminant exposure in ospreys (Clark et al. 2001). Concentrations of organochlorine pesticides and PCBs in randomly collected osprey eggs declined compared to eggs collected in 1989 (Steidl et al. 1991b), and eggshell thickness was comparable to that of the pre-DDT era. Prior to the current study, only 1 osprey egg had been analyzed for organochlorine contaminant exposure from the Delaware State portion of the Bay (Wiemeyer 1988; 4.6 $\mu\text{g/g}$ PCBs and 5 $\mu\text{g/g}$ *p,p'*-DDE), and no eggs had been analyzed from the most contaminated regions in northern Delaware and southern Pennsylvania.

While many of the most harmful organochlorine chemicals were banned several decades ago, their residues or metabolites still persist in water, sediment, and biota. The water, sediment and fish in the tidal portion of the Delaware River and Bay still contained high concentrations of toxic chemicals as recently as 2000 (Kausch et al. 2000). In addition, other bioaccumulative chemicals are still being released (e.g., perfluorinated compounds, polybrominated diphenyl ethers) that are potentially hazardous to wildlife (Kannan et al. 2001; Hale et al. 2001; Law et al. 2002), yet their toxicological effects are not well known. Remarkably, contaminant exposure and effects in ospreys nesting within the Delaware boundary of the Bay and north of the C&D Canal in the Delaware River had yet to be comprehensively studied. Based upon this data gap, and high concentrations of toxic chemicals found in Delaware River finfish, we conducted the first

large-scale ecotoxicological evaluation of ospreys on the Delaware River and Bay, and Coast, covering over 300 km of shoreline.

OBJECTIVES

The objectives of this study were to (1) monitor osprey productivity as an integrator of multiple stressors, (2) evaluate contaminant exposure of ospreys nesting in the Delaware River and Bay, (3) identify gradients in contaminants in osprey eggs and compare them to those seen in water and sediment, and (4) to compare the concentration of contaminants in osprey eggs in this region to values in other areas of the United States.

METHODS

Study Area

This study spanned from the Atlantic Ocean and the tidal areas in the shallow Inland Bays to the freshwater non-tidal Delaware River near East Stroudsburg, Pennsylvania. The Delaware Estuary is a “drowned-riverbed” estuary, characteristic of the middle-Atlantic coastal habitat. For this study, the Delaware River and Bay region was divided into 4 segments (Figure 1) based on water quality data collected by the Delaware River Basin Commission (DRBC) and the U.S. Environmental Protection Agency (USEPA; Kausch et al. 2000; USEPA 1997). The riverine segment in the Easton-East Stroudsburg region of Pennsylvania supports all uses of water and was not classified as threatened (Kausch et al. 2000). The northern segment of the Bay includes the upper tidal portion of the Delaware Bay from Trenton, New Jersey 90 km south to the C&D Canal, Delaware; most of this area has serious water quality problems, high vulnerability to pollution, and does not support aquatic life in some locations (Kausch et al. 2000). The central segment includes central and southern Delaware Bay from the C&D Canal, Delaware, 130 km

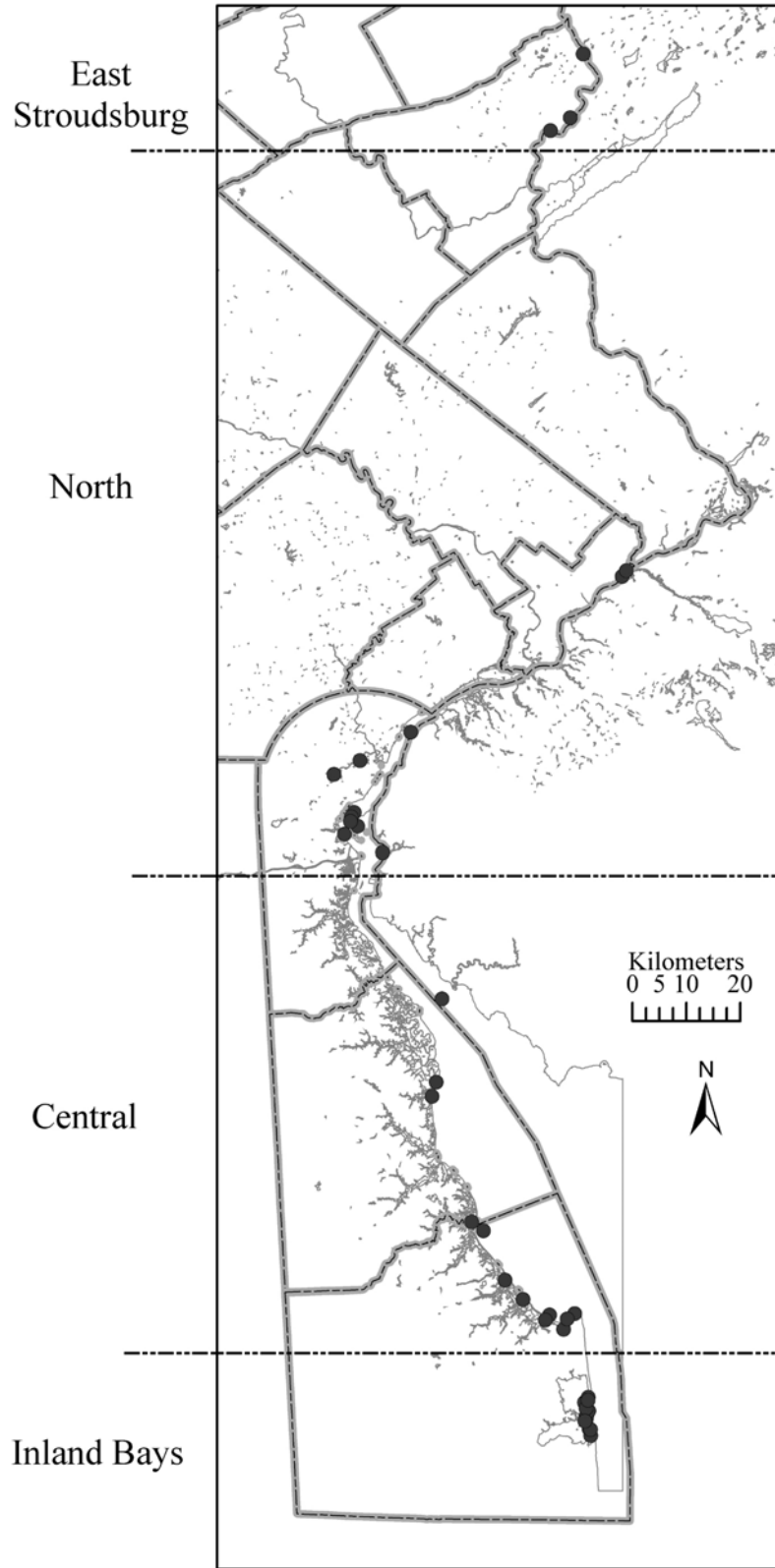


Figure 1. Osprey nest sampling sites and study segments.

south to Cape Henlopen, Delaware; this area has serious water quality problems and high vulnerability to pollution (Kausch et al. 2000). This segment supports aquatic life, but is threatened in some areas (Kausch et al. 2000). The southern segment encompasses Rehoboth and Indian River Bay (Inland Bays) along the Atlantic coast of Delaware; this segment has less serious water quality problems, but high vulnerability to pollution. Locations of osprey nests in the study area were identified by a fixed-wing aircraft survey conducted by U.S. Geological Survey (USGS) and U.S. Fish and Wildlife Service (USFWS) in May of 2001, boat and ground searches in 2002, communication with State and Federal agencies, and conservation groups. All known nests were checked to determine if they were occupied (ospreys present on the nest) in 2002.

Data Collection

A subset of ospreys nesting on navigation markers and other fixed structures (N=39) over the 300 km study area from the Delaware Inland Bays north to East Stroudsburg, Pennsylvania, were studied from March through August 2002. Three nests were sampled in the riverine segment, and twelve nests were sampled in the northern, central, and southern segments (Figure 1). Several nests in the central segment of the study area were located on or near National Wildlife Refuges and Delaware State Wildlife Management areas. All nests were intensively monitored (i.e., measures of contaminant exposure were collected and reproductive observations were made through fledging) at 7-14 day intervals by climbing the nest to directly observe the contents or by viewing the contents with a pole-mounted mirror, using vehicles or boats to access the nest sites when necessary. Sample collection at several sites in the riverine and northern

regions required assistance from bucket trucks and professional climbers to access the nests.

Upon completion of a clutch, a single random sample egg was collected from each nest. It was weighed, measured (length and breadth), and the contents were examined and then frozen (-20°C) for contaminant analysis. The remaining eggs in each nest were monitored by brief nest inspections in order to determine hatching success. Numerous studies have demonstrated that concentrations of organochlorine contaminants in the sample egg are representative of concentrations in remaining eggs of the clutch (Spitzer et al. 1978; Custer et al. 1983, 1990; Wiemeyer et al. 1988). This relatively standardized technique has been utilized extensively to evaluate reproductive effects of organochlorine and metal contaminants in a variety of free-ranging avian species (reviewed by Ohlendorf and Hothem 1995; Blus 1996). Addled eggs (N = 6) were opportunistically collected from nests, processed, and analyzed by the same methods as fresh eggs. The data from the addled eggs were not included in the contaminant results tables, but are discussed where appropriate.

After hatching, nest visits were continued at 7-14 day intervals to determine nestling survival. At approximately 40 days of age, a randomly selected nestling was briefly removed from each nest. Culmen length and body weight were measured at this time, and general condition of the nestling was recorded. A blood sample (5-7 ml; brachial venipuncture; Patuxent Wildlife Research Center Contaminants Technical Operating Procedure 48) was obtained for genetic damage assessment. Blood samples were snap-frozen in liquid nitrogen immediately after collection and transferred to a -80 °C freezer within 24 hours. The young were returned to their nest as quickly as possible,

usually within 10 minutes. Survival of all nestlings was monitored until fledging (day 50-60). Evidence of egg and nestling loss due to predation, adverse weather, and other such disturbances was noted.

Analytical Methods

Contents of sample eggs were chemically analyzed for 25 organochlorine pesticides or metabolites, total PCBs, arylhydrocarbon receptor-active PCB congeners, and Hg (Qian et al. 1998; Sericano et al. 1998; Cromartie et al. 1975; Wade et al. 1988) by contract laboratories (Geochemical and Environmental Research Group and Trace Element Research Laboratory, College Station, Texas) under the rigorous quality assurance and quality control guidelines of the USFWS Patuxent Analytical Control Facility. For the organochlorine pesticides or metabolites and PCBs, egg contents were homogenized, anhydrous sodium sulfate was added, and the mixture was extracted with dichloromethane. The extract was evaporated, concentrated, and then dissolved in hexane. Alumina/silica gel chromatography was used to fractionate this solution, followed by high-resolution gas chromatography with electron gas capture detection. For mercury analysis, egg homogenates were freeze-dried and analyzed by cold vapor atomic absorption spectroscopy. The minimum detection limit for organic chemicals ranged from 0.0015 to 0.025 $\mu\text{g/g}$; the minimum detection limit for mercury was approximately 0.005 $\mu\text{g/g}$. Toxic equivalents (TEQs) were calculated using a weighted average of *Ah* receptor-active PCB congener concentrations in egg extracts (Van den Berg et al. 1998).

Other contaminants (e.g., perfluorinated compounds, polybrominated diphenyl ethers) were quantified by collaborators at Exygen Research (State College,

Pennsylvania) and at the Virginia Institute of Marine Sciences (R.C. Hale) in a subset of 15 freeze-dried egg homogenates selected to represent the entire study area geographically.

Freeze dried egg homogenates were analyzed for perfluorosulfonates and perfluorocarboxylic acids (C8-C12) by extraction with methanol, followed by addition of activated carbon, and then filtration. The extract was analyzed using high pressure liquid chromatography followed by MS/MS electrospray on an Hewlett Packard 1100 (Avondale, PA) with a Jones Chromatography Genesis C-8 50 x 2.1 x 4 μm column, interfaced to a Micromass Quattro Ultima (Beverly, MA). Laboratory control spikes, matrix spikes, and 6-point calibration curves were used to ensure quality control. The limit of detection was approximately 0.0005 $\mu\text{g/g}$, and limit of quantification was 0.010 $\mu\text{g/g}$.

Details of polybrominated diphenyl ether (PBDE) analysis are found in Hale et al. (2001) and Rattner et al. (in press). In brief, PCB congener 204 was added to the freeze-dried egg homogenates, which were then extracted with methylene chloride. The extracts were purified on a silica gel solid-phase extraction column. The extract was eluted with hexane in the silica gel column, with the initial product discarded, followed by elution with 60:40 hexane:methylene chloride. The product of this elution was solvent exchanged to hexane, and separated on a GC (Varian 3400, Palo Alto, CA) with a 60 m DB-5 column (J&W Scientific, Folsom, CA; 0.25 m film, 0.32 ID). Injections of carrier gas and helium were conducted in the splitless mode. The internal standard was pentachlorobenzene, and the data were corrected based on PCB congener 204 recovery. Concentrations of PBDEs were quantified by GC/MS in the full scan ionization mode

(Varian 4D ion trap; Palo Alto, CA). The minimum limit of quantification was approximately 100 pg/g ww, recovery of PCB congener 204 ranged from 75 to 106% and recovery of PBDE congener 77 ranged from 71 to 139%. One egg misfired in the GC/MC in the first run, and therefore, results of 14 egg samples are reported.

Biomarkers of Exposure and Effects

Because the stage or state of egg samples (e.g., freshly laid, embryonated, addled or failed to hatch) varied, the volume of each egg was estimated and the concentrations of contaminants in eggs were adjusted to account for moisture loss that occurs during incubation (Stickel et al. 1973). Wet weight concentrations of contaminants were adjusted to account for moisture loss.

Eggs were cut in half to empty the contents; the eggshells were rinsed with distilled water (membrane left intact) and dried at room temperature. Eggshell thickness, a biomarker of exposure to principally *p,p'*-DDE, was determined as the average of three measurements around the equator using a dial gauge micrometer accurate to 0.01 mm (model 1010M, L.S. Starrett Co., Athol, MA; Wiemeyer et al. 1988; PWRC Contaminants Technical Operating Procedure 20).

Genetic damage was assessed in blood samples based on the coefficient of variation of cellular DNA content using flow cytometry methods (Custer et al. 1994). Briefly, nuclear suspensions from blood samples were treated with RNase and the RNA and DNA were stained with propidium iodide. A Coulter Profile II flow cytometer with a 488 nm Argon laser was used to quantify the nuclear fluorescence and side scatter. In the G1 peak, mean and standard deviation of 10,000 individual cells was recorded and coefficient of variation calculated for each cell (half peak and full peak coefficient of

variation). Cells with a high level of side scatter were not included in the calculations. High coefficients of variation indicate that an organism has a high level of genetic damage, possibly due to exposure to a genotoxic chemical (e.g., PAHs, metals). This method of detecting genotoxic effects of chemicals on chromosome damage within cells has performed well compared to other methods of assessing genotoxicity in laboratory studies with mammals (Wagner et al. 1998).

Statistical Methods

Prior to initiation of the study, a power analysis was conducted to determine the minimum number of eggs required per study segment ($\alpha = 0.05$, $\beta = 0.80$, $\Delta = 2$). The analysis was done using contaminant concentrations from osprey eggs collected in the Chesapeake Bay in 2000 and 2001 (Rattner et al. in press). It was determined that a collection of 12 eggs per segment would allow us to accurately identify significant differences in contaminant concentrations among regions (only 3 eggs were collected in the riverine segment due to the small breeding population and inaccessible nesting structures in that segment).

Differences continuously distributed variables including contaminant concentrations, culmen length, body weight, full peak DNA coefficient of variation, and eggshell thickness in these variables among study areas were determined using analysis of variance and Tukey's HSD method of multiple comparisons. Variables were tested for the assumptions for ANOVA (Levene's HOV test, Shapiro-Wilkes statistic, examination of plot of residuals vs. predicted values) and log transformed to normalize data where appropriate. Reproductive success was determined using traditional methods (number of occupied nests, successful pairs, young fledged per successful nest, young per occupied

nest), and by the Mayfield method (Mayfield 1961, 1975). Productivity differences among regions were determined using Fishers Exact Test with a Bonferroni correction where appropriate (Everitt 1977). Pearson correlation was used to examine the relation between *p,p'*-DDE concentrations in eggs and eggshell thickness.

The relation between contaminant concentrations in the sample egg and the fate of the remaining eggs in that nest was examined using logistic regression (Hosmer and Lemeshow 1989). All contaminants in the model (*p,p'*-DDE, chlordane and metabolites, heptachlor epoxide, and total PCBs) were correlated, so a principle components analysis was utilized to obtain one or two orthogonal explanatory variables. These particular contaminants were selected for modeling because they were found in highest concentrations in eggs relative to their known effect levels. Logistic regression methods were also utilized to determine if contaminant exposure affected osprey nest activity (number of nests with eggs laid), in conjunction with other habitat factors, and to look for geographic trends in contaminant concentrations (Toschik et al. in prep.). All statistical analyses were conducted using SAS V8 (SAS Institute Inc., Cary, North Caroline) or SPSS software, with the exception of the Mayfield estimates, which were based on methods from Bart and Robson (1982).

RESULTS

Nest success and productivity among regions was generally similar and near or within the range estimated to be necessary to maintain a local osprey population (Poole 1989). Greatest concentrations of most organochlorine, polybrominated, and perfluorinated contaminants were found in eggs from the northern study segment. Despite

regional differences in contaminant concentrations among study segments, the eggshell thickness and genetic damage biomarkers did not differ among study segments.

Reproductive Success

Significantly more eggs were lost in the north than in the central segment ($p < 0.05$; “eggs lost” does not include eggs found addled in nests), although number of eggs laid, percent of eggs hatched, percent of eggs lost, number of nestlings lost, percent of nestlings fledged, and number of nests failed were not significantly different among the segments (Table 1). Despite all efforts to monitor nests closely, several individuals disappeared from nests during the period of time when they could have been an unhatched egg or a newly hatched chick. Estimates of laying and hatching dates were not precise enough to determine the exact stage at which these eggs disappeared (N=3 in south, N=4 in the north). In general, more eggs than nestlings were lost, so to err on the side of caution, results are reported as if all unknown individuals were lost at the egg stage.

Morphological and Biochemical Endpoints

Body weight and culmen length at time of blood collection were greater in the northern segment (1631 ± 38.7 g, 30.3 ± 0.459 mm) than in the southern segment (1357 ± 65.2 g, 27.9 ± 0.613 mm; $p < 0.05$). Since both parameters were greater in the north, this probably indicates that nestlings from southern Delaware were either slightly younger at time of measurement, or that the birds were actually smaller in the south due to latitudinal variation in body size. A similar relationship between body size and culmen length and latitude was seen in ospreys in the Chesapeake Bay in 2001 (Rattner et al. in press). All nestlings appeared to be in good health, with no lesions or other abnormalities observed.

Table 1. Productivity of sampled osprey nests in Delaware and Pennsylvania, 2002

	<u>South</u>	<u>Central</u>	<u>North</u>	<u>Riverine</u>
Active Nests Sampled	12	12	12	3
Eggs Laid	38	40	39	9
Eggs Naturally Incubated	26	28	27	6
Fate of Eggs				
Lost-Unknown	4	1	11	0
Lost-Predated	2	1	2	0
Lost-Weather	0	2	0	0
Failed to Hatch	0	2	2	1
Hatched (%)	20 (77%)	22 (79%)	12 (44%)	5 (83%)
Hatchability (%)**	20/20 (100%)	22/24 (92%)	12/14 (86%)	5/6 (83%)
Fate of Nestlings				
Predated	4	0	0	0
Found out of nest	1	0	0	0
Disappeared	1	5	0	2
Fledged (%)	14 (70.0%)	17 (77%)	12 (100%)	3 (60%)
Successful Nests	9 of 12	9 of 12	9 of 12	2 of 3
Fledglings/Active Nest	1.17	1.42	1.00	1.00
Mayfield Method Estimates				
Egg laying and incubation period	N = 12	N = 12	N = 12	N = 3
Daily survival rate \pm SE	0.998 \pm 0.070	0.995 \pm 0.084	0.992 \pm 0.099	1
Survival rate to hatching (A)	0.914	0.807	0.740	1.000
Nestling period	N = 11	N = 10	N = 8	N = 3
Daily survival rate \pm SE	0.996 \pm 0.068	0.998 \pm 0.082	1	0.987 \pm 0.166
Survival rate to fledging (B)	0.822	0.899	1.00	0.503
Nest success (A x B)	0.751	0.725	0.740	0.503
Probability of an egg hatching given that the nest is successful (C)	0.950	0.857	0.842	1.00
Probability of young living to 53 days given that the nest is successful (D)	0.737	0.944	0.750	1.00
Egg success (A x B x C x D)	0.526	0.587	0.467	0.503
Mean clutch size (E)	3.17	3.33	3.25	3.00
Mean number of young surviving to 53 days (A x B x C x D x E)	1.66	1.96	1.52	1.51
Mean number of young surviving to 53 days, less sample egg (A x B x C x D x (E-1))	1.14	1.37	1.05	1.01

*unknowns were considered lost at the egg stage (N=3 inland bays, N=4 north)

**Hatchability is the number of eggs that remain in nests throughout incubation that hatch

A = daily survival to the 39th power accounting for a 35 to 43 day incubation period

B = daily survival to the 53rd power accounting for 50-55 day nestling period

C = the number of eggs that hatched in successful nests divided by the total number of eggs in successful nests

D = the number of nestlings that fledged in successful nests divided by the total number of nestlings in successful nests

One nestling in the Inland Bays appeared to develop more slowly than other nestlings (based on weight and age), though this may have been due to inexperienced parents. Fishing line was observed in several nests, and one nestling in Indian River Bay had to be cut free from fishing line entangling its legs and wings on two consecutive nest visits.

Eggshell thickness (Table 2) was significantly greater in eggs from the riverine segment than from the south or the north, however, this may be more of a reflection of the small sample size of eggs from the riverine segment than of true differences. The central segment had significantly thicker eggshells than the northern segment, which is consistent with the difference in *p,p'*-DDE concentrations. No significant correlation was found between *p,p'*-DDE concentration and eggshell thickness.

Full peak coefficient of variation in blood flow cytometry assays did not differ among segments, suggesting cell genetic damage did not vary among segments, based on this biomarker. Full peak coefficient of variation is presented rather than half peak because the data had relatively little noise.

Contaminant Exposure

Osprey eggs collected from the northern segment generally had significantly greater concentrations of organochlorine pesticides or metabolites (Table 2),

perfluorinated compounds (Table 3), and polybrominated diphenyl ethers (Table 4) than eggs from other regions. Total PCBs (the sum of 209 congeners) were also greatest in the northern segment, with the minimum northern concentration actually exceeding the maximum concentrations from all other sites (Table 5). Mercury was detected in all eggs at moderately low concentrations (Table 2).

The following compounds were detected only in eggs collected from the northern segment, at concentrations $<0.01 \mu\text{g/g}$: *o,p'*-DDE (N = 2), gamma-chlordane (N = 12), and pentachloro-anisole (N = 1). The following contaminants were not detected in eggs from any segment: aldrin, heptachlor, delta-BHC, gamma-BHC, alpha-BHC, toxaphene, Aroclor 1242, and PCB congeners 30, 63, and 114. Aroclor 1248 was detected in 1 egg from the riverine segment and 1 egg from the north, at concentrations $< 0.5 \mu\text{g/g}$.

Concentrations of perfluorononanesulfonate exhibited a north to south gradient, with highest concentrations in the north, decreasing towards the south ($p < 0.05$; Spearman rank-order correlation, latitude vs. perfluorononanesulfonate). Perfluorodecanoic acid, perfluoroundecanoic acid, and perfluorododecanoic acid were significantly greater ($p < 0.05$, Tukey's HSD method of multiple comparison) in the north segment compared to both the southern and central segments. In the north, perfluorooctanoic acid (N=6), perfluorononanesulfonate (N= 6), perfluorundecanesulfonate (N=6), and perfluorododecanesulfonate (N=3) were detected, but below the limit of quantification. In the central segment, perfluorooctanoic acid (N=6), perfluorononanesulfonate (N=6), perfluorundecanesulfonate (N=2), and perfluorododecanesulfonate (N=1) were detected but below the limit of quantification. In eggs from the southern segment, perfluorooctanoic acid and perfluorononanesulfonate

Table 2. Wet weight concentrations ($\mu\text{g/g}$) of organochlorine pesticides and metabolites and mercury, and biomarker responses in osprey eggs collected in the Delaware River and Bay

	South	Central	North	Riverine
	(N = 12)	(N = 12)	(N = 12)	(N = 3)
Matrix Analyte ($\mu\text{g/g}$)	Geometric Mean Extremes N Quantifiable	Geometric Mean Extremes N Quantifiable	Geometric Mean Extremes N Quantifiable	Geometric Mean Extremes N Quantifiable
Egg	0.352 ^C	0.852 ^B	1.77 ^A	0.656 ^{ABC}
<i>P,p'</i> -DDE	0.172-1.20 12	0.349-4.61 12	0.785-3.84 12	0.394-1.05 3
<i>P,p'</i> -DDD	0.017 ^C 0.006-0.038 12	0.057 ^B 0.022-0.216 12	0.182 ^A 0.089-0.323 12	0.031 ^{BC} 0.027-0.036 3
<i>P,p'</i> -DDT	0.003 ND-0.004 4	0.003 0.001-0.013 12	0.004 0.002-0.016 12	0.003 ND-0.003 2
<i>O,p'</i> -DDE	- ND 0	- ND 0	- ND-0.003 2	- ND 0
<i>O,p'</i> -DDT	0.007 ^B 0.002-0.011 12	0.010 ^B 0.005-0.019 12	0.028 ^A 0.018-0.052 12	0.009 ^B 0.003-0.016 3
<i>O,p'</i> -DDD	0.012 ^C 0.005-0.018 12	0.020 ^B 0.011-0.039 12	0.038 ^A 0.024-0.066 12	0.017 ^{BC} 0.015-0.019 3
Dieldrin	0.004 ^C 0.002-0.012 12	0.008 ^B 0.003-0.026 12	0.041 ^A 0.026-0.084 12	0.012 ^{BC} ND-0.025 2
Endrin	- ND 0	0.001 0.001-0.005 12	0.002 0.001-0.005 12	- ND 0
Heptachlor epoxide	0.004 ^B 0.001-0.013 12	0.007 ^B 0.003-0.015 12	0.021 ^A 0.014-0.036 12	0.007 ^B 0.004-0.012 3

	0.004 ^{AB}	0.003 ^B	0.007 ^A	0.004 ^{AB}
<i>alpha</i> -chlordane	ND-0.006	0.001-0.010	0.002-0.018	ND-0.005
	3	12	12	2
	0.004 ^C	0.010 ^B	0.027 ^A	0.005 ^{BC}
<i>cis</i> -Nonachlor	0.002-0.011	0.003-0.023	0.014-0.052	0.004-0.005
	12	12	12	3
	0.002 ^C	0.005 ^{AB}	0.010 ^A	0.003 ^{BC}
<i>trans</i> -Nonachlor	0.001-0.011	0.002-0.009	0.003-0.030	0.002-0.005
	12	12	12	3
	0.005 ^B	0.008 ^B	0.025 ^A	0.010 ^B
Oxychlordane	0.001-0.010	0.004-0.016	0.016-0.046	0.006-0.014
	12	12	12	3
	0.006	0.005	0.008	0.004
Mirex	0.001-0.058	0.002-0.013	0.004-0.014	0.003-0.006
	12	12	12	3
	-	0.002	0.005	-
HCB	ND	0.002-0.002	0.004-0.014	ND
	0	2	12	0
	0.05	0.09	0.06	0.04
Hg	0.02-0.14	0.02-0.27	0.03-0.23	0.030-0.061
	12	12	12	3
Blood Biomarker - Full Peak	4.05 ± 0.12	3.98 ± 0.075	3.98 ± 0.065	3.90 ± 0.10
Coefficient of Variation, mean ± SE	9	9	9	2

Eggshell Thickness (mm, mean ± SE)	0.468 ± 0.009	0.501 ± 0.011	0.454 ± 0.010	0.527 ± 0.008
% difference from pre DDT era	-9.3	-0.8	-10.1	4.4

ND = Not detected; - = no mean calculated because contaminant was detected in fewer than half the samples; means with different capital letter superscripts are significantly different by Tukey's HSD method of multiple comparison, $p < 0.05$

Table 3. Wet weight concentrations (ng/g) of perfluorinated compounds in osprey eggs collected in the Delaware River and Bay*

	South (N = 2)	Central (N = 6)	North (N = 6)	Riverine (N = 1)
Analyte (ng/g)	Geometric Mean Extremes N Quantifiable	Geometric Mean Extremes N Quantifiable	Geometric Mean Extremes N Quantifiable	Geometric Mean Extremes N Quantifiable
	-	10.0	27.8	-
Perfluorononanoic acid	2.38 1	3.30-29.1 6	4.49-50.1 6	NQ 0
Perfluorodecanoic acid	2.66 ^B 1.63-4.33 2	7.43 ^B 5.23-12.6 6	29.8 ^A 9.54-69.5 6	- 4.74 1
Perfluoroundecanoic acid	7.00 ^B 4.91-9.98 2	31.8 ^B 13.9-86.8 6	121 ^A 66.0-221 6	- 12.8 1
Perfluorododecanoic acid	1.89 ^B 1.58-2.67 2	4.69 ^B 2.69-7.28 6	31.8 ^A 10.8-72.7 6	- 3.69 1
Perfluorooctane-sulfonate	37.8 ^B 33.8-42.3 2	96.9 ^{AB} 37.4-370 6	293 ^A 127-799 6	- 122 1
Perfluorodecane-sulfonate	- 1.24 1	4.96 ^B 2.20-11.6 6	26.8 ^A 8.99-52.4 6	- 8.98 1

*A subset of 15 samples were selected for these analyses based on geographical distribution, rather than equal representation of study segments; N=2 Southern segment, N=6 Central segment, N=6 North segment, N=1 Riverine segment; NQ = Not quantifiable; - = no mean calculated because contaminant was detected in fewer than half the samples; means with different capital letter superscripts are significantly different by Tukey's HSD method of multiple comparison, $p < 0.05$

Table 4. Wet weight concentrations (ng/g) of polybrominated diphenyl ethers in osprey eggs collected in the Delaware River and Bay*

Analyte (ng/g)	South	Central	North	Riverine
	Mean Extremes N	Mean Extremes N	Mean Extremes N	Mean Extremes N
	Quantifiable	Quantifiable	Quantifiable	Quantifiable
Congener 47	46.6 ^B 43.0 - 50.1 2	124 ^{AB} 90.7 - 231 6	240 ^A 223 - 258 5	- 227 1
Congener 99	7.93 ^B 6.20 - 9.66 2	18 ^{AB} 8.61 - 52.8 6	122 ^A 45.8 - 228 5	- 140 1
Congener 100	12.4 ^B 10.5 - 14.3 2	34.5 ^{AB} 22.2 - 85.1 6	102 ^A 62.3 - 155 5	- 82.0 1
Congener153	5.32 ^B 2.80 - 7.83 2	10.8 ^{AB} 5.93 - 28.2 6	45.9 ^A 25.0 - 93.3 5	- 61.2 1
Congener154	7.87 ^B 3.44 - 12.3 2	12.5 ^{AB} 6.92 - 21.0 6	41.4 ^A 29.1 - 68.5 5	- 43 1
Hexa-a**	2.08 ^B 1.43 - 2.72 2	3.32 1.73 - 5.28 6	2.99 1.97 - 3.96 5	- 2.27 1
Hexa-c**	- ND 0	2.15 ND - 2.65 4	2.60 ND - 3.21 4	- 2.50 1
Total PBDEs	82.2 ^B 70.9 - 93.5 2	206 ^{AB} 141 - 429 6	561 ^A 442 - 820 5	- 557 1

*A subset of 14 samples were selected for these analyses based on geographical distribution, rather than equal representation of study segments; N=2 Southern segment, N=6 Central segment, N=5 North segment, N=1 Riverine segment; **hexa-a and hexa-c are hexa-brominated compounds that have not yet been specifically identified; - = no mean calculated because contaminant was detected in fewer than half the samples; means with different capital letter superscripts are significantly different by the Savage score test and Wilcoxin 2-sample t-test, $p < 0.05$; concentrations are corrected for recovery of PCB204 surrogate standard and loss of moisture during incubation

Table 5. Wet weight concentrations of total PCBs and *Ah* receptor-active PCB congeners in osprey eggs collected in the Delaware River and Bay

Analyte	South	Central	North	Riverine
	(N = 12)	(N = 12)	(N = 12)	(N = 3)
	Geometric Mean Extremes N Quantifiable	Geometric Mean Extremes N Quantifiable	Geometric Mean Extremes N Quantifiable	Geometric Mean Extremes N Quantifiable
Total PCBs (µg/g)	1.44 ^C 0.469-2.43 12	2.44 ^B 1.23-5.15 12	8.68 ^A 5.50-14.5 12	4.38 ^{AB} 4.17-4.70 3
Aroclor 1254 (µg/g)	0.551 ^C 0.212-1.20 12	0.829 ^{BC} 0.470-1.80 12	3.52 ^A 2.23-6.53 12	1.67 ^{AB} 0.835-2.36 3
Aroclor 1260 (µg/g)	0.876 ^C 0.259-1.44 12	1.55 ^B 0.676-4.35 12	5.01 ^A 2.48-8.29 12	2.38 ^{AB} 1.72-3.34 3
Ratio Aroclor 1254/1260	0.63 0.427-1.00 12	0.53 0.111-0.819 12	0.70 0.428-1.37 12	0.70 0.250-1.38 3
PCB 77 (pg/g)	97 36-366 12	135 37-263 12	238 42-752 12	195 105-292 3
PCB 81 (pg/g)	698 170-2,634 12	482 142-7,616 12	585 190-2,050 12	357 344-370 3
PCB 105 (ng/g)	17.1 ^B 5.44-34.2 12	24.2 ^B 11.4-43.9 12	96.4 ^A 58.9-179.9 12	57.5 ^A 36.5-111 3
PCB 118 (ng/g)	72.9 ^B 25.4-143 12	114 ^B 48.3-205 12	411 ^A 262-701 12	25.9 ^A 201-343 3
PCB 126 (pg/g)	200 ^B 103-383 12	228 ^B 103-449 12	557 ^A 284-964 12	367 ^{AB} 287-504 3
PCB 128 (ng/g)	22.2 ^C 7.49-42.9 12	33.6 ^{BC} 14.4-63.1 12	117 ^A 73.5-179 12	68.1 ^{AB} 55.7-97.3 3
	16.6 ^C	25.0 ^{BC}	116 ^A	53.7 ^{AB}

PCB 156 (ng/g)	4.95-26.3 12 15.7 ^C	9.31-46.5 12 28.1 ^B	62.2-251 12 139 ^A	39.8-89.6 3 60.3 ^B
PCB 158 (ng/g)	5.01-28.1 12 189	11.6-61.1 12 552	78.6-237 12 3999	41.7-92.2 3 4773
PCB 166 (pg/g)	44-3,351 12 11.9 ^B	118-793 12 18.3 ^B	2,265-9,203 12 57.4 ^A	1,999-8,887 3 21.6 ^B
PCB 167 (ng/g)	3.63-20.4 12 -	8.04-34.9 12 96	38.5-87.6 12 75	16.8-27.7 3 -
PCB 169 (pg/g)	103 1 2.00 ^C	ND-111 3 3.95 ^B	39-133 12 13.6 ^A	ND 0 3.91 ^{BC}
PCB 189 (ng/g)	0.618-3.55 12 163 ^C	1.65-9.39 12 240 ^{BC}	7.60-21.4 12 769 ^A	2.94-5.07 3 475 ^{AB}
PCB 138/160 (ng/g)	48.3-332 12 32.7 ^C	100-489 12 59.9 ^B	449-1,303 12 239 ^A	428-505 3 110 ^{AB}
PCB 170/190 (ng/g)	9.68-55.0 12 108	25.1-154 12 90.3	139-408 12 160	73.9-142 3 97
TEQs (SWB) (pg/g)	45.5-299 12	35.2-828 12	68.4-341 12	78.6-126 3

ND = Not detected; - = no mean calculated because contaminant was detected in fewer than half the samples; means with different capital letter superscripts are significantly different by Tukey's HSD method of multiple comparison, $p < 0.05$

(N=2) were detected but below the limit of quantification.

Total PBDEs and PBDE congeners were analyzed; four as yet unidentified mixtures of hexa-BDEs (“hexa-a – d”) and one penta-BDE mixture (“penta-a”) were quantified. Total PBDEs, congeners 47, 99, 100, 153, 154, and mixture hexa-a were detected in all eggs analyzed (N=14); while mixture hexa-b was not detected in any

sample, and mixture hexa-c was only detected in 1 of 1 egg from the riverine segment, 4 of 5 eggs from the northern segment, and 4 of 6 eggs from the central segment. The only egg containing quantifiable concentrations of penta-a was collected from a nest located on a channel marker at the mouth of Little Creek, which drains parts of Dover Air Force Base. Total PBDEs exhibited a latitudinal trend, with highest concentrations in the north, decreasing towards the south ($p < 0.0001$; Spearman rank-order correlation, latitude vs. total PBDEs). All congeners and total PBDEs were significantly higher in eggs collected from nests in the northern region compared to those collected from the central region. The proportion of total PBDEs as congener 47 exhibited a distinct latitudinal trend ($p < 0.05$; Spearman rank-order correlation), with the proportion of congener 47 decreasing from south to north (maximum percent of total PBDEs accounted for by congener 47 was 69%, minimum was 31%).

Relationship of Contaminants to Reproduction

A logistic regression model of productivity and contaminants (using the principal components) found that fledging success could not be predicted by contaminant exposure, while hatching success could. Toxic equivalents were not included in the model because they were not significantly correlated with either hatching or fledging success. Interestingly, hatching success could be explained by contaminants in either of 2 ways, a simple multiplicative model, or a model utilizing principal components analysis. Hatching success was a function of the product of p,p' -DDE * total PCBs * total chlordane metabolites * heptachlor epoxide, which is the same as the sum of the log transformed concentrations of these contaminants ($p < 0.05$). The equation for the logistic model predicting hatching success was:

$$\ln(p/(1-p)) = 0.3012 + 0.4782 * [\log_{10}(p,p\text{'-DDE)} + \log_{10}(\text{total chlordanes metabolites}) + \log_{10}(\text{heptachlor epoxide}) + \log_{10}(\text{total PCBs})].$$

The relationship is represented visually in Figure 2. In the logistic model using the first principal component produced effectively the same equation to describe hatching success. This was because the first principal component (which explained 91.8% of the variation) weighted the four chemical groups (log transformed concentrations) almost equally. While these contaminants concentrations in eggs are predictive of hatching success, this should not be viewed as a cause and effect relationship. Perfluorinated compounds and total PBDEs did not have significant effects

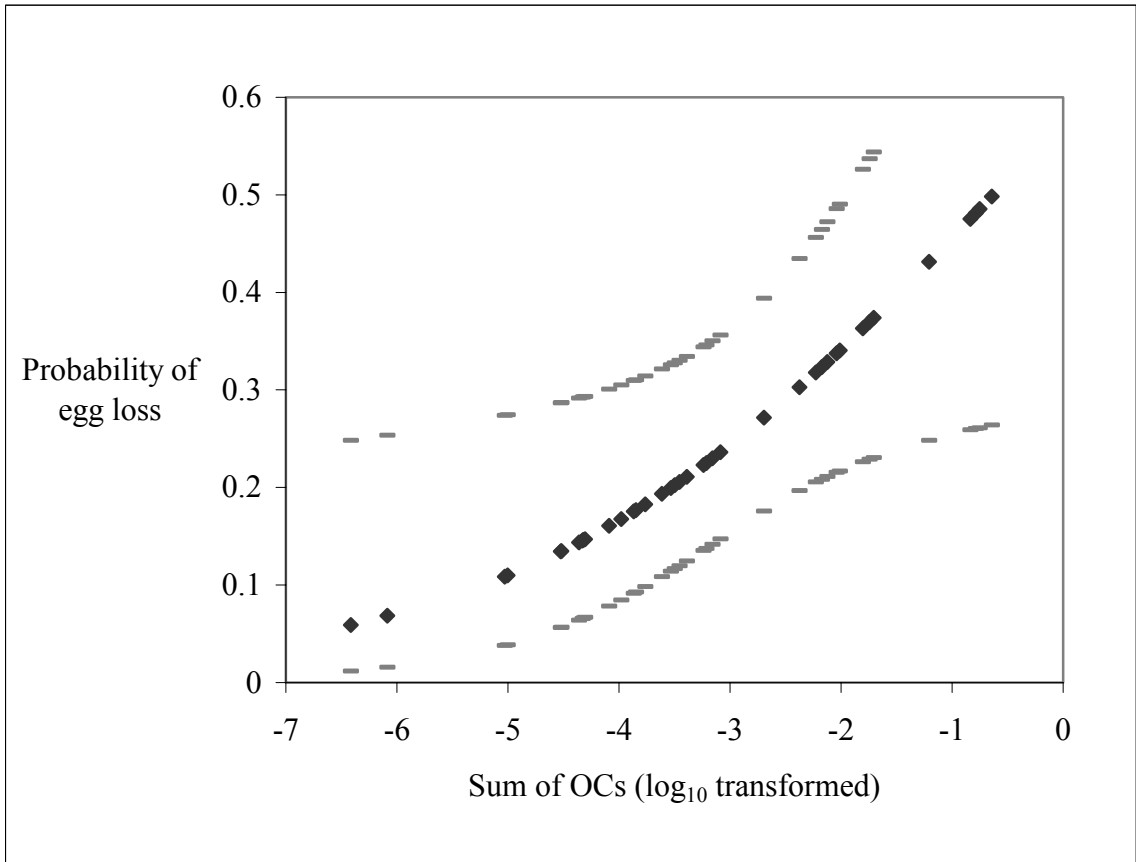


Figure 2. Predicted probability of egg loss, based on the sum of log transformed contaminants (total PCB, *p,p*'-DDE, chlordanes and metabolites, and heptachlor epoxide); as the total contaminant burden increases, the probability of egg loss increases. Diamonds are the predicted probabilities; dashes are the 95% confidence intervals.

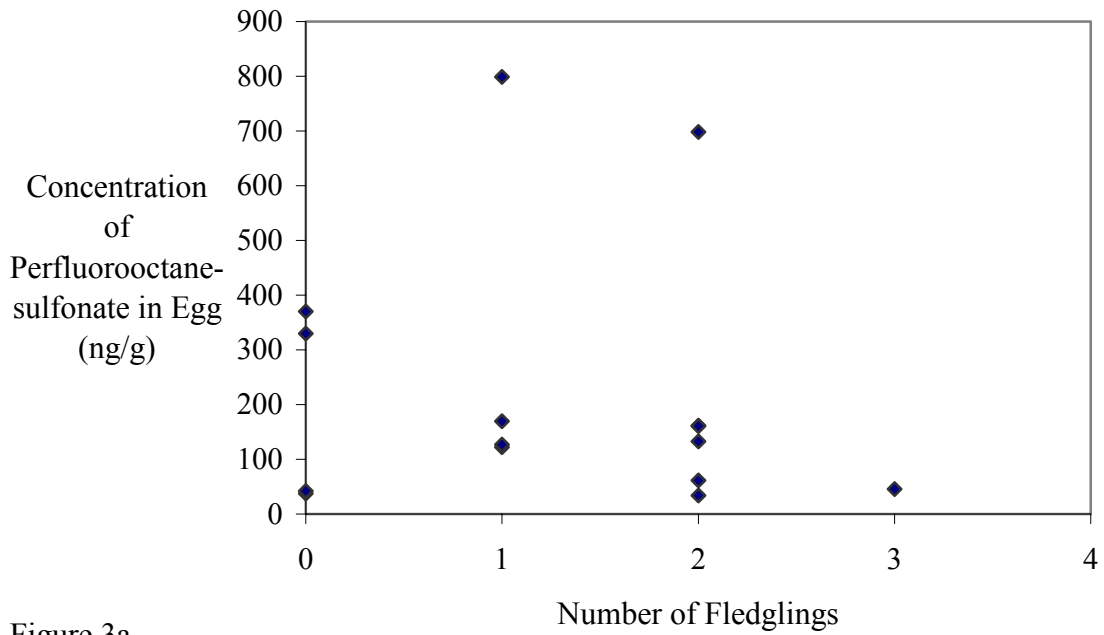


Figure 3a.

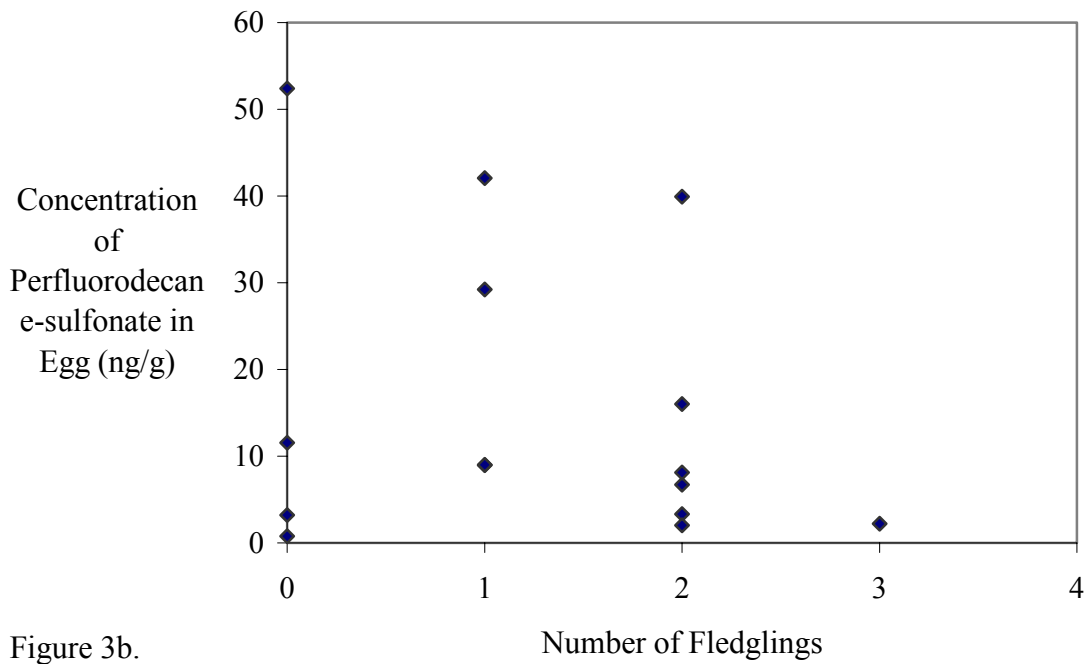


Figure 3b.

Figure 3. Concentrations of selected perfluorinated compounds versus the number of fledglings per nest.

on fledglings produced per active nest, though the patterns in the data (esp. perfluorodecanesulfonate, perfluorodecanoic acid, perfluorononanoic acid, and perfluorooctanesulfonate) indicate this might be worth further research with a larger sample size (Figure 3 a, b). The model was also run excluding nests where timing of egg or nestling loss precluded exact determination of what was lost (egg or chick). The hatching success model was not altered greatly by this, and the logistic regression model with the principal component was still a significant predictor of hatching success. The results of the logistic regression model for hatching success make sense in light of individual nest observations. The 3 nests that failed in the southern segment all exhibited evidence of predation, and all had relatively low levels of *p,p'*-DDE and total PCBs. In the central study area, one of the nests that failed was apparently blown off the channel marker; the nestlings disappeared from a second nest in this region, suggestive of predation. However, the third nest that failed was located on the channel marker at the mouth of Little Creek, a tributary that drains part of Dover Air Force Base. The sample egg and an addled egg from that nest contained high concentrations of *p,p'*-DDE (4.3 µg/g and 4.6 µg/g, respectively); these *p,p'*-DDE concentrations exceeded the 4.2 µg/g threshold associated with 15% eggshell thinning. Total PCBs in these eggs were low (4.4 and 4.8 µg/g). In the northern segment cormorants predated one nest. However, a second nest in the northern region near New Castle failed, and had high *p,p'*-DDE and PCBs (3.6 µg/g *p,p'*-DDE and 14.5 µg/g PCB). The sample egg collected from the third failed nest, further north by Trenton, also contained high *p,p'*-DDE (3.8 µg/g) and PCBs (11.3 µg/g). An addled egg from this nest contained 4.6 µg/g *p,p'*-DDE and 12.6 µg/g PCBs. The sample egg from the nest that failed in the riverine segment had low *p,p'*-DDE (0.39

µg/g) and moderate PCBs (4.29 µg/g). In summary, of the 10 nests that failed, 6 nests exhibited evidence of predation or weather-related loss, 3 had exceptionally high *p,p'*-DDE concentrations in the sample egg (2 of these 3 nests also contained addled eggs), and 1 was lost for unknown reasons.

DISCUSSION

Productivity

In view of the magnitude of differences in contaminant concentrations, the similarity in productivity among regions was unexpected. However, the contaminant concentrations were apparently below thresholds that adversely affect fledging success. The larger number of eggs lost in the northern segment may reflect greater predation pressure, competition between ospreys and cormorants for nesting structures^{*}, or even stress from multiple factors, including contaminant exposure. The productivity for all regions was within or above the range estimated to maintain a population for ospreys on the east coast of the U.S. (0.8 – 1.15; Poole 1989), although productivity in the northern and riverine segments was marginal at 1 fledgling/active nest. Productivity was generally greater than in 1989 (< 0.8 fledglings/active nest; Steidl 1991a), and the south and central segments were similar to 1994-1998 productivity for ospreys in the Salem and Maurice River areas of New Jersey (1.1 fledglings/active nest; Clark et al. 2001).

The logistic regression model indicated that concentrations of *p,p'*-DDE, chlordane and metabolites, heptachlor epoxide, and total PCBs were predictive ($p < 0.05$) of hatching success, but not fledging success.

* Cormorants were observed breeding on an osprey nest and on all levels of the skeletal channel marker that held the original nest. The osprey eggs were found broken on the platform, presumably eaten by the cormorants during a hostile nest takeover. Cormorants also occupied several other channel markers in the northern segment near New Castle, Delaware, that were of suitable design for osprey nesting.

Recovery of the osprey population as a whole in the Delaware Bay is still incomplete. For example, we observed only 6 active nests in Kent County in 2002, well below the historic 90 nests observed in the same region prior to the widespread use of organochlorine pesticides, even though it has been decades since their use was discontinued (Hess et al. 2000). Assuming the management goal for this species is to have the population return to near historic levels, there is much left to be done in restoring their habitat beyond the Inland Bays region. Examination of individual nest failures indicates most are due to predation, with contaminants a close second in the more highly polluted areas.

Morphological and Biochemical Endpoints

The concentration of *p,p'*-DDE (log transformed) was not significantly correlated with eggshell thickness (N = 39, $p = 0.23$, $r^2 = -0.17$). This may have been due to the small number of samples with *p,p'*-DDE above 2 $\mu\text{g/g}$ or with greater than 10% eggshell thinning. The similarity of mean eggshell thickness between northern segment and southern segment eggshells was curious, and not expected based on contaminant concentrations in eggs from the two sites. Eggshell thickness of all eggs (N = 3) from the riverine segment was slightly greater than would be expected, even from pre-DDT era eggshell measurements (see Wiemeyer et al. 1988).

Full peak and half peak coefficient of variation (FPCV) results indicate similar levels of genetic damage among study areas, but does not eliminate the possibility that some genetic damage is occurring. Others have found that half peak CV in avian blood did not have an apparent dose-response relationship at low levels of contaminant exposure (Wickliffe and Bickham 1998). FPCV measurements for osprey blood in the

present study were slightly greater than those found in black-crowned night-heron (*Nycticorax nycticorax*) chick blood in one study (means ranged from 3.44 to 3.86; Custer et al. 1994), and somewhat lower than those found in mink dosed with crude oil or fuel oil (means ranged from 4.17 to 5.07), though without comparisons of multiple species from a single site it is not clear if this difference is species specific or indicative of site differences.

The presence of fishing line in osprey nests is a serious problem in the Delaware and Chesapeake Bays (see Rattner et al. in press). Anglers can often be found fishing from boats tied to markers and platforms with active osprey nests, creating not only a disturbance to the breeding birds, but a known hazard from discarded tackle and fishing line. Education of anglers regarding proper disposal of fishing equipment and enforcement are especially important in areas with high densities of both ospreys and anglers, such as the Inland Bays and Lewes, Delaware.

Organochlorine Pesticides or Metabolites

In general, organochlorine pesticide or metabolite concentrations differed among segments as expected based on sediment, water and fish contaminant exposure data, with the north containing the greatest concentrations, followed by the central then the south. However, the eggs from the riverine segment were slightly more contaminated than expected. The use of the osprey as a monitor of local contaminant exposure is further supported by these results, as it is unlikely that the latitudinal trends seen in egg contaminant exposure are due to contaminant exposure on the wintering grounds (one would expect ospreys to be distributed somewhat differently relative to each other on wintering grounds compared to breeding grounds). For most organochlorine pesticides or

metabolites, concentrations in eggs from the riverine segment were similar to those from the central and southern segments. The source of DDE was historical based on the proportion of *p,p'*-DDT to other metabolites (< 0.1% of sum of all metabolites of DDT). Contaminant exposure for ospreys in the northern segment was significantly greater than that for all other regions for many contaminants, including *p,p'*-DDD, *o,p'*-DDT, *o,p'*-DDD, dieldrin, heptachlor epoxide, *cis*-nonachlor, and oxychlordan; exposure in the northern segment was greater than all other sites excluding the riverine segment for *p,p'*-DDE.

The most recent data on osprey contaminant exposure from the Delaware Bay region prior to this study consisted of a small sample of eggs, below the area with the greatest contaminant exposure in the present study. While concentrations of heptachlor epoxide and oxychlordan in osprey eggs collected in the Salem River, New Jersey were quite similar to those in the present study, *p,p'*-DDE concentrations were slightly lower and the maximum dieldrin concentration was lower than the minimum concentration in the present study (Clark et al. 2001).

Two of the eggs sampled in the present study were from nests on Prime Hook National Wildlife Refuge (central segment); they contained *p,p'*-DDE concentrations of 0.69 and 0.57 µg/g wet weight. Compared to an egg collected on the refuge in 1974 (*p,p'*-DDE 5 µg/g wet weight; Wiemeyer et al. 1988), *p,p'*-DDE exposure has declined substantially. In contrast, concentrations of *p,p'*-DDE in eggs in the northern part of the river and bay (geometric mean 1.77 µg/g, range 0.785 – 3.84 µg/g) were similar to those seen in eggs from Wisconsin and Michigan between 1980 and 1996 (Karasov and Meyer 2000; Ewins et al. 1999), similar to fresh eggs collected in the New Jersey portion of the

Delaware Bay in 1989 (Steidl et al. 1991b), and greater than those observed in 1998 (Clark et al. 2001; maximum *p,p'*-DDE concentration observed was 1.61 µg/g).

Concentrations of *p,p'*-DDE differed significantly among regions and were generally near effect thresholds in the central and northern regions, with several eggs containing concentrations expected to cause 10-15% eggshell thinning. In fact, *p,p'*-DDE concentrations in 9 of 12 eggs (75%) collected in the northern segment and 3 of 12 (25%) collected in the central segment were within the 95% confidence interval for 10-15% eggshell thinning (Wiemeyer et al. 1988); eggs collected in the Anacostia and Potomac Rivers in Maryland and Virginia had only 9 of 16 eggs (56%) in this category (Rattner et al. in press).

Mirex concentrations in the osprey eggs were well below concentrations expected to have effects on avian species. However, the maximum concentrations of mirex in eggs from the north, central and southern segments were above the 0.01 µg/g threshold in food considered protective for mammalian wildlife (Eisler 2000). As osprey eggs are predated by avian and mammalian species, this presents some cause for concern, although osprey eggs are an unlikely primary food source for any predator. Other studies have documented a larger proportion of addled eggs than random eggs from the mid-Atlantic region contained detectable concentrations of mirex and dieldrin (Steidl et al. 1991b), however, this was not the case in the present study, in which similar occurrence and concentrations of dieldrin and mirex were observed both addled and fresh eggs. Presence of low concentrations of endrin in all eggs from the central and northern regions is suggestive of an historical source in the main Delaware Bay area, which is consistent with the extensive agriculture in this area.

PCBs

Concentrations of PCB congeners 158, 167, and 189 in eggs from ospreys in the northern segment were significantly greater than that for all other regions; exposure in the northern region was greater than all other sites excluding the riverine segment for total PCBs, Aroclor 1254, Aroclor 1260, and PCB congeners 105, 118, 106, 128, 156, 170/190, and 138/160. Total PCBs, Aroclors, and co-planar congeners PCB concentrations in eggs from the riverine segment were most similar to those from the north and central regions. The continuing exposure to PCBs in the Delaware ospreys was not detected in a recent study of birds on the New Jersey side of the Bay (Clark et al. 2001). PCB concentrations in the northern and East Stroudsburg regions remain in the range of 1989 samples from the Delaware Bay (Steidl et al. 1991).

Despite the significant differences among regions for total PCB concentrations, all concentrations were well below expected effect threshold for birds (300 $\mu\text{g/g}$ in brain, which would translate to a somewhat higher concentration than in eggs; Bryan et al. 1987). However, all twelve eggs in the northern segment and one egg from the central segment had total PCB concentrations over 2 $\mu\text{g/g}$, the FDA maximum for human consumption in fish (USEPA 1992). Notably, the greatest PCB concentration detected in an egg from the central segment (5.15 $\mu\text{g/g}$) was from the most northern nest in the segment, located on a channel marker at the mouth of the Leipsic River, adjacent to Bombay Hook National Wildlife Refuge. This could present potential risk to mammalian predators, though it is unlikely it would affect avian predators.

Two of the eggs sampled in the present study were from nests on Prime Hook National Wildlife Refuge (central segment), and contained concentrations of 2.36 and

1.31 µg/g of PCBs. Compared to an egg collected on the refuge in 1974 (PCBs 4.6 µg/g; Wiemeyer et al. 1988), PCB concentrations have declined. In contrast, concentrations of PCBs in eggs in the northern part of the river and bay were similar to those seen in eggs from Wisconsin and Michigan between 1980 and 1996 (Karasov and Meyer 2000; Ewins et al. 1999), similar to fresh eggs collected in the New Jersey portion of the Delaware Bay in 1989 (Steidl et al. 1991b), and greater than those observed in 1998 (Clark et al. 2001). In fact, the lowest PCB concentration in 2002 eggs from the northern region (5.50 µg/g) was greater than the maximum concentration seen in 1998 eggs in the New Jersey portion of the Bay (4.45 µg/g; Clark et al. 2001).

Perfluorinated Compounds

The occurrence of PFOS compounds was different in osprey eggs collected in the present study from the Delaware Bay compared to osprey eggs collected from the Chesapeake Bay (Rattner et al. in press), with acids detected more often in Delaware Bay eggs and sulfonates detected more often in Chesapeake Bay eggs. Some of the acids with lower number of carbons (4 – 8) may have volatilized from the Delaware Bay egg samples when they were freeze-dried before analysis, however, this process should not have affected the acids with greater number of carbons or the sulfonates. Concentrations of perfluorooctanesulfonate in the osprey eggs were similar to concentrations seen in egg yolks and blood serum and plasma in other fish-eating water birds in the U.S., Japan, and Korea (Kannan et al. 2001; Kannan et al. 2002a).

Little is known about the direct and indirect effects of perfluorinated compounds on wildlife, despite evidence that diverse wildlife species are exposed to these compounds around the world (Kannan et al. 2001; 2002a, b; Rattner et al. in press).

Perfluorodecanoic acid is a hepatotoxin in rats, known to elevate phosphocholine in the liver (Adinezhadeh et al. 1999) and to induce the CYP4A subfamily of isoenzymes (Chinje et al. 1994). Perfluorodecanoic acid also causes reduced maternal and fetal weight, and can reduce fetal viability in mice (Harris and Birnbaum 1989). Controlled laboratory and field experiments should be undertaken to better assess the hazard of these compounds to wild birds.

Polybrominated Diphenyl Ethers

The latitudinal trend detected in PBDEs in eggs collected from the Delaware Bay and River may reflect the different mobility of the congeners and the distance of the ospreys from the source (R. Hale personal communication). Congener 47 is the lightest and most mobile congener, making it more likely to be found further from the source than other congeners, such as BDE 99 (which was found in the greatest proportions in the northern and riverine regions). The results of this study indicate that while BDEs are found throughout the Delaware Bay and River, the source of the compounds is most likely in the Pennsylvania or New Jersey portion of the Delaware Bay and River watershed.

The lipophilicity, potential estrogenic activity, and dramatic increase of PBDEs in the environment have focused a great deal of attention on these chemical compounds in the scientific community (Alaee and Wenning 2002). However, no information exists on the toxicity of these compounds to avian species, and very few exposure data have been collected. Exposure data from herring gulls (*Larus argentatus*) in the Great Lakes indicate that concentrations of PBDEs are increasing exponentially in wildlife (Norstrom et al. 2002). Laboratory in vitro and mammalian studies indicate that the hydroxylated

metabolites of PBDEs and some PBDE congeners may affect thyroid hormone function, induce cytochrome P450, alter the liver/body weight ratio, affect the Ah receptor (similar to some PCB congeners), affect motor behavior, learning and memory, exhibit immunotoxicity (de Witt 2002). Some of the most important effects of PBDEs have been induced by congener 47, which is also the most abundant congener in the Delaware osprey eggs (31 to 69% of total PBDEs), and the congener with the highest bioavailability (de Witt 2002).

Presence and abundance of congeners 47, 99, 100, 153, and 154 in cormorant (*Phalacrocorax carbo*) livers collected in England and Wales (Law et al. 2002) was similar to that seen in osprey eggs from the Delaware River and Bay. Concentrations in the cormorant livers were most similar to concentrations in osprey eggs from the southern study region, and much lower than concentrations in osprey eggs from the central and northern regions. Relatively low concentrations of PBDEs were also found in starling (*Sturnus vulgaris*) muscle from Sweden, and in store bought and dosed chickens (de Witt 2002). Osprey muscle samples collected in Sweden from birds found dead contained 2140 ng/g lipid PBDEs, an exceptionally high concentration of PBDEs (Jansson et al. 1993; Sellstrom et al. 1993). Concentrations of total PBDEs and individual congeners in Delaware osprey eggs were within the range of concentrations observed in herring gull eggs collected from the Great Lakes region in 2000, though maximum concentrations in the Great Lakes samples were nearly double the greatest concentrations observed in the present study (Norstrom et al. 2002).

Mercury

Mercury was detected in all eggs at moderately low concentrations (Table 2), in the same range as in osprey eggs from the Chesapeake Bay in 2000 and 2001 (Rattner et al. in press) and the Delaware Bay in 1998 (Clark et al. 2001).

CONCLUSIONS AND MANAGEMENT RECOMMENDATIONS

While the outlook for ospreys in Delaware River and Bay is quite good, the population is still facing challenges in its recovery from the past population decline. Concentrations of many chemicals in the osprey eggs have decreased in the last few decades (e.g., *p,p'*-DDE); however, human impacts on this population are still measurable, and chemicals known to be harmful to laboratory animals are consistently being detected in the osprey eggs. Further research to develop effect concentrations of perfluorinated chemicals and polybrominated diphenyl ethers in birds should be a priority for comparison with this region and other urban wildlife habitats. A decline in habitat quality factors (e.g., water clarity) in the Delaware River and Bay could put even greater stress on the already struggling central and northern portions of this region, a realizable risk with potential dredging activity in the main shipping channel. Future monitoring of the nesting activity, breeding success, and contaminant exposure (esp. perfluorinated chemicals and polybrominated diphenyl ethers) of ospreys throughout the Delaware Bay and River should provide wildlife managers with an indicator of the health of the coastal habitat.

CHAPTER 3: EVALUATION OF OSPREY HABITAT SUITABILITY AND INTERACTION WITH CONTAMINANT EXPOSURE

ABSTRACT

Ospreys have been the focus of conservation efforts since their dramatic population decline attributed to DDT and related chemicals in the 1960's. Several recent studies of ospreys nesting in the United States have indicated improved reproduction. However, the density of breeding ospreys varies greatly among locations, with some areas seemingly habitable but not occupied. Due to concerns about pollution in the highly industrialized lower Delaware River, we evaluated contaminant exposure and productivity in ospreys nesting on the Delaware River and Bay in 2002. We characterized habitat in the coastal zone of Delaware and the area around the river in Pennsylvania using data we collected as well as information provided by state and federal sources. Habitat was characterized based on locations of active osprey nests in Delaware and Pennsylvania. Fish biomass, water clarity, water depth, land use and land cover, nest availability, air pollution, wind speed, and contaminants in osprey eggs and sediments were evaluated for use in a nest activity model. The nest activity model was compared to existing habitat models for ospreys; the model developed in this study performed markedly better. Results showed that the presence of active nests was associated with water depth, water clarity, distance to an active osprey nest, and presence of urban land use, while hatching success was associated with principal components based on organic contaminants in eggs. This study provides some guidelines for resource managers and local conservation organizations in management of ospreys and in development of habitat models that are appropriate for other piscivorous and marsh nesting birds.

INTRODUCTION

Delaware Bay's value to wildlife has been recognized with its inclusion in the National Estuary Program, the Western Hemisphere Shorebird Reserve Network, the "Last Great Place" list of The Nature Conservancy, and its listing as a Wetland of International Significance (Dove and Nyman 1995). The Delaware Bay is highly industrialized, especially near Philadelphia, Pennsylvania, yet it has agricultural lands, intensive poultry farming, and extensive coastal marshes interspersed along the bay. Even though many harmful organochlorine chemicals were banned decades ago, their residues and metabolites still persist in sediment, water, and biota in Delaware Bay and elsewhere (McCoy et al. 2002).

Avian species are often the subject of contaminant research (i.e., Furness and Greenwood 1993; Kushlan 1993; Walker 1983) because of their sensitivity to contaminants. Eggshell thinning, as a result of exposure to the pesticide metabolite *p,p'*-DDE, caused catastrophic declines in several species of birds, notably the osprey (Spitzer et al. 1978). Lead poisoning (Sanderson and Bellrose 1986) was a major cause of mortality in waterfowl for several decades, before the introduction of non-toxic shot. Chlordane poisoning continues to cause mortality in passerines and raptors, even though chlordane was among the chemicals banned decades ago (NYDEC 2001). This sensitivity to contaminants makes birds useful indicators of ecosystem health.

Recent studies of osprey in the nearby Chesapeake Bay indicate organochlorine contaminant concentrations are below the threshold expected to affect productivity (Rattner et al. in press). However, ospreys nesting in historically contaminated sites were at lower densities than those at the reference site (Rattner et al. in press). Initial

observations of ospreys breeding in the Delaware River and Bay indicated a similar disparity in osprey nesting density. One explanation for this is that the habitat quality and contaminant concentrations combine to have sub-lethal effects on the distribution and success of breeding osprey among available nesting habitats.

Characterizing habitat based on wildlife use provides a tool for population evaluation and management, and important insight into resource selection (Boyce and McDonald 1999). Numerous techniques for evaluating habitat use have been described and tested (see Alldredge and Ratti 1986; Alldredge and Ratti 1992; Boyce and McDonald 1999; Bender et al. 1996). In this paper, we use logistic regression models to predict osprey nest activity and hatching success based on habitat parameters, including contaminant exposure.

The primary requirements for a breeding pair of osprey are a safe nest location and access to fish. Safe nest locations must be protected from human disturbance, competitors (i.e., bald eagles), and predators (i.e., raccoons, great-horned owls; Ewins, 1997). Factors such as water clarity and depth (Dove and Nyman 1995; Poole 1989), fish abundance (Spitzer 1978; McLean and Byrd 1991), wind speed (Machmer and Ydenberg 1990), and contaminants in fish (Steidl et al. 1991b), can affect access to food, in turn affecting the suitability of available nesting habitat. Ospreys also prefer nest sites near other active osprey nests (Lohmus 2001), although they are not considered colonial breeders.

While ospreys have been observed on a diversity of natural and artificial nest structures, nearly 93% of the ospreys in the Chesapeake Bay are nesting on artificial nesting structures, and some subpopulations are nesting exclusively on artificial

structures (Watts et al. in press). Historically, osprey populations have been limited by nest site availability in areas of the Chesapeake Bay; the ospreys in this situation appeared to be initiating breeding at an older age than is normally expected (> 3 yrs; Poole 1989) and new platforms installed in these areas were immediately occupied (Watts et al. in press). These observations of the Chesapeake Bay osprey population suggest that ospreys are not limited completely to artificial nesting structures, however they may have a strong preference for them. The availability of platforms and channel markers in Delaware could similarly be affecting that osprey population.

Several studies have addressed effects of individual habitat parameters for ospreys (e.g., Lohmus 2001; Levenson and Koplin 1984; Spitzer 1978), yet no single study has considered the combination of contaminant exposure and multiple habitat suitability factors. It is likely that more than one factor is affecting the ospreys breeding the Delaware River and Bay and elsewhere. This study attempts to address multiple factors that may affect the Delaware Bay osprey populations. It includes analysis of existing habitat quality data, as well as data collected on habitat quality, contaminant exposure, and productivity, in conjunction with the contaminants study.

Two other methods exist for predicting osprey productivity from environmental variables. The first method, the Habitat Suitability Index (HSI) model (Vana-Miller 1987), was developed based on osprey life history literature. The model was designed to quantify habitat quality for ospreys nesting on lakes and rivers. In the HSI method, the highest score represents the best habitat for an osprey and is based on measures of human activity, water clarity, water surface obstruction, fish abundance, and number of potential nesting structures (Vana-Miller 1987). The second method, also a model of osprey

habitat use, was designed by the U.S. Fish and Wildlife Service (USFWS) to quantify habitat quality for coastal and estuarine nesting ospreys in the Gulf of Maine (Banner and Schaller, 2000). The goal of the Gulf of Maine (GOM) model was to provide guidelines for habitat conservation, with the highest score being associated with optimal habitat, and therefore, those areas have the highest conservation priority. This model is based on land use, proximity to water, water depth, and proximity to active nests. However, these models are not generally extendable to other areas, since the Vana-Miller model was not fit to actual nest site data or tested with field data, and in the GOM model only a limited set of habitat variables were examined. Neither model addressed other important variables, such as site contamination (as evidenced by concentrations of contaminants in sediments), contaminant burdens of adult and juvenile ospreys, and productivity of ospreys at active nest sites. From a broader estuarine health perspective, Summers (2001) has suggested that water quality and local pollution including chemicals in the water and air, water clarity, nitrogen and phosphorus may also contribute to reduced habitat quality.

Based on a need to better understand osprey habitat requirements to maximize success of management efforts, we undertook an evaluation of the osprey habitat in terms of both breeding activity and breeding success throughout the coastal area around Delaware River and Bay.

OBJECTIVES

The objectives of this study were (1) to evaluate the relative importance of contaminant exposure of ospreys nesting in the Delaware River and Bay to other habitat variables, (2) to explain the difference in osprey nest density between northern and

southern Delaware River and Bay by producing a habitat suitability model for estuarine breeding ospreys based on field data, (3) to evaluate existing habitat suitability models for osprey and compare them to the model developed from this research, and (4) provide management recommendations regarding osprey habitat in the Delaware River and Bay.

METHODS

Study Area

The Delaware River and Bay (Figure 4) were selected as the study area because of the interest in managing the ospreys in this region and the availability of data on nest site locations and breeding activity over a large scale. Delaware Bay also provides a unique mix of urban, agricultural and ‘natural’ habitats, all with breeding ospreys and gradients of other habitat factors of interest for ospreys (contaminant exposure, water depth, water clarity, etc.).

Methods for Evaluating Osprey Habitat Suitability: Data Preparation

Parameters considered for the Delaware River and Bay osprey habitat model included those used in the original HSI model and the GOM habitat model and several additional parameters, because neither of these models completely addressed the habitat in the Delaware River and Bay. Data collection and manipulation methods are described below. Water clarity, depth, fish biomass, sediment contaminants, and air pollution were averaged in a 3 km buffer around osprey nests, because usually ospreys nest within 3-5 km from water (Poole 1989). Ospreys are capable of nesting up to 10 km from water (Lohmus 2001), but rarely do this. A 0.2 km buffer around the nests was selected for

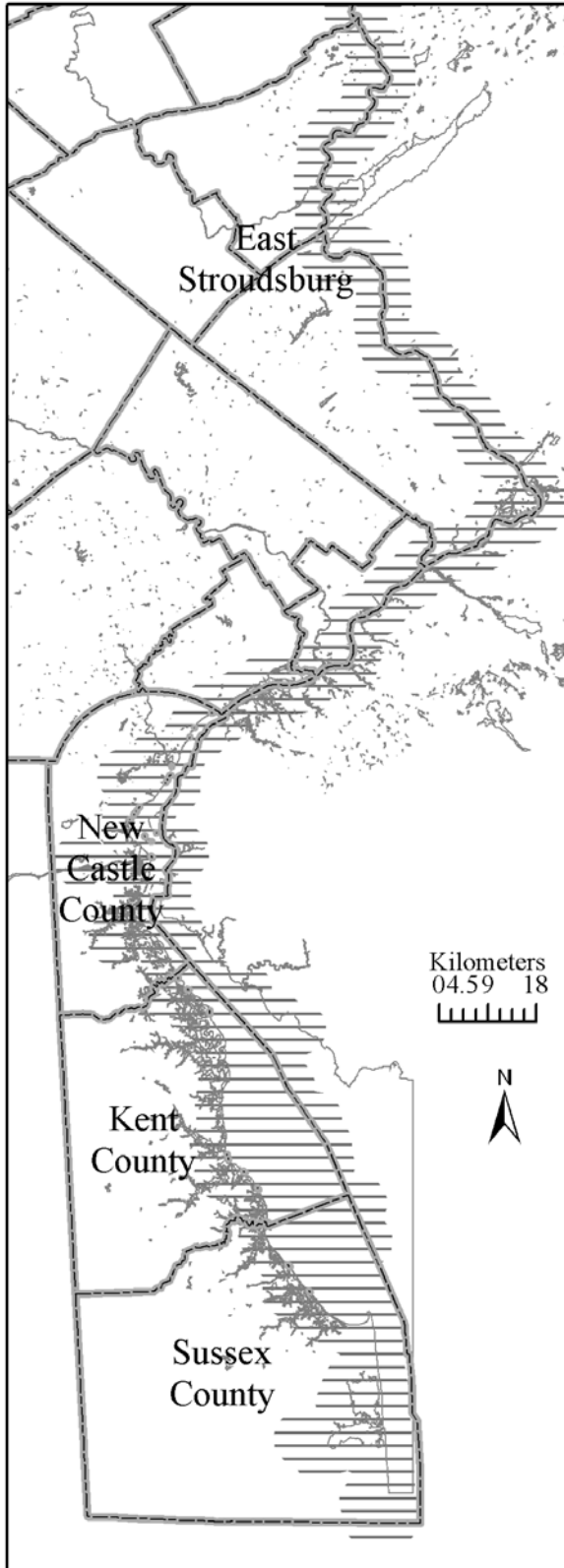


Figure 4. Delaware Bay and River; general study area indicated by horizontal lines.

describing land use and land cover variables, because proximity of these habitat characteristics to the nest are suspected to be important. Random points were generated and analyzed in the same manner as the potential and active nest locations, to allow us to determine if the ospreys were using habitat in a significantly different pattern than would be expected from a random distribution of nest sites.

Water Clarity

We collected water clarity data for the Delaware Bay and River and the Inland Bays (as secchi disk depth - single measurement with a 20 cm black and white disk) at 2.5 km intervals alongshore approximately 0.5 km offshore of Delaware (June 16-20, 2002). When the bottom was visible from the boat, the water depth was assigned as the secchi disk depth.

Comparable water clarity data for the

river between Trenton, New Jersey and Artificial Island, New Jersey, were not available, and so were interpolated. A latitudinal trend and latitude-longitude interaction ($p < 0.0001$, ANOVA) in secchi disk depth was detected, although no longitudinal trend was found. The slope of the line describing water clarity spatial interactions was significantly different above versus below 40° north latitude. Consequently, the data were divided at 40° N latitude, and fit to two separate linear regressions. North of 40° the water clarity was related to latitude and longitude (R-square = 0.926, $p < 0.0001$). South of 40° the water clarity was related to latitude, longitude, and the interaction of latitude and longitude (R-square = 0.914, $p < 0.0001$). Water clarity was interpolated for the north and south regions using their respective regression equations to predict the clarity every 0.01 degrees (≈ 855 m) throughout the study area. The two sets of predicted points were then merged to form a continuous data set for the entire study area. The predicted points were clipped to areas identified as water on the Maryland/Delaware/New Jersey GAP project Land Use and Land Cover (MDN LULC) layer and averaged within a 3 km circular buffer around each point or nest site.

Nest Availability

Efforts were made to identify all possible active and potential nest sites for ospreys in Delaware and southeastern Pennsylvania region bordering the Delaware River and Bay. This included a fixed-wing aircraft survey was conducted by the U.S. Geological Survey (USGS) and USFWS in May of 2001, boat and ground searches in 2002, and frequent communication with state and federal agencies, and conservation groups. All known nests were checked to determine if they were active in 2002. We also surveyed sites considered potential nest locations for ospreys. These were platforms

specifically installed for ospreys, fixed location U.S. Coast Guard aids to navigation (not including buoys or other unsuitable marker types), and other sites at which active osprey nests had been observed between 2000 and 2002.

Locations were recorded with a handheld Garmin GPS 12XL (Olathe, Kansas) in most cases. Several locations were estimated from a map based on site information. Nest sites were plotted in ArcView 8.2; several of the positions of the nest locations required minor adjustments based on field observations of the nest site. Nests were considered active if eggs or chicks were observed in the nest at any time during the 2002 breeding season (April 1 to August 15, 2002). All other sites were classified as inactive. Nests were observed at least once during the breeding season, although two subsets of nests were monitored more frequently as part of the productivity study (visits at 10 day intervals) and as part of a local osprey monitoring program (single visit each in spring and in summer). Only nests within the Delaware and Pennsylvania state borders were included in this analysis for logistical reasons.

Water Depth

Bathymetry for the Delaware Bay was acquired from the National Oceanic and Atmospheric Administration (NOAA) bathymetry digital elevation model (DEM; 1998). Bathymetry data for the portion of the river in northern Delaware and in Pennsylvania were provided as point data in CAD files from the Army Corps of Engineers (ACOE). The precision of the NOAA data layer was sufficient to distinguish 1 meter intervals. The DEM was converted to a grid and then converted to point coverage to permit merging of this dataset with ACOE and Delaware Coastal Programs bathymetry data.

The ACOE data were converted from feet to meters, and point files that did not align properly after conversion into shapefiles were manually georeferenced in ArcView 8.2. Original projection of the data was NJ State Plane FIPS 2900 NAD83; the data were converted to NAD 83 Zone 18 GCS North American to match other data layers. The ACOE and NOAA dataset spatially overlapped where the bay and river meet. A subset of 500 points from the overlapping area was analyzed to determine if the layers aligned properly. A linear regression analysis was used to do the comparison (ACOE depth = $-2.84 + 0.75 \cdot \text{NOAA depth}$, R-square = 0.623). Based on this regression, we adjusted the ACOE depths to match the NOAA depths before joining them.

Bathymetry point data for Rehoboth Bay was provided by the Delaware Coastal Management Programs (DCMP; D.B. Carter, pers. comm.). The original projection of the NOAA and DCMP data layers was NAD 27 Zone 18; both layers were converted to NAD 83 Zone 18 GCS North American to match other data layers.

For all areas of the River and Bay and for the coastal bays, potential nest locations and random points were buffered to 3 kilometers around each nest site. Average depth was calculated from all points that fell within each buffer area.

Land Use and Land Cover

Land use and land cover (LULC) maps were provided by the Maryland/Delaware/New Jersey (MDN) GAP Analysis Project (2002). The original map had 62 LULC classifications based on 30-meter grid cells, and was projected in NAD 83 UTM Zone 18. A 0.2 km buffer around potential nest locations and random points was used for descriptive statistics about local land use at a potential or active nesting site. The 0.2 km buffer was selected based on what is believed to be a reasonable distance

around a potential nest site for an osprey to consider when selecting the nest site. Ospreys will nest within 50 to 100 meters of other ospreys (Poole 1989), which suggests that the local area of importance around a nest is relatively small. The LULC categories within the buffers around each nest were evaluated using Pearson Chi-Square test of independence. Those LULC classes that occurred in a greater proportion of active than inactive nests or those that were used in different proportions than were predicted from the inactive and random points were retained for further analysis. Based on this initial evaluation of the data, subsequent analyses were simplified by combining the classes “row crops” and “pasture/hay” into a single “agriculture” class; “tidal high marsh,” “tidal marsh,” “tidal tallgrass marsh”, and “dune grassland” into “coastal marshes;” “lowland pine woodland,” “tidal maritime shrublands,” and “nontidal maritime shrublands” into “shrubs”; and leaving “urban” and “water” in classes by themselves. All other LULC classes were excluded from the analyses because they fell within less than 5% of the buffers of active nests. For the nest activity model, land use classes were identified as present or absent from the buffers for each inactive and active nest site. For the productivity model, the percent of the buffer occupied by each land class was quantified.

Fish Biomass

Fish population estimates were obtained from state fisheries trawls, and were used to make a map of estimated fish biomass using ArcView 8.2. The Delaware State Fisheries Programs conducted trawls in 2001 for juvenile fish with a 16-foot otter trawl at 33 stations from Wilmington south to Cape Henlopen, mostly well offshore (Michals and Greco 2002). The statistics provided by the trawls included species identifications and the length frequencies within each species caught at each sampling station. Data were

summarized as total biomass of fish in the size and species range available to ospreys, averaged over monthly trawls in July and August 2001. Specifically, size range of fish included in the biomass calculation was 0.5-4.5 kg; all species with the exception of crabs, seahorses, sharks, and rays were included in the biomass count. Mass of fish was calculated using known length-weight relationships, found on www.fishbase.org or elsewhere in the scientific literature. Biomass of several fish species that did not have a defined length-weight relation was estimated with the length-weight relation of a species in the same genus. Kriging (spherical model) and nonlinear regression were used to interpolate areas where fish were not directly sampled. Average fish biomass was calculated in the 3 km buffer around each potential nest site.

Wind Speed

Wind speed data were obtained from weather stations maintained by the Delaware State Coastal Programs (n=6) and NOAA (data obtained through the National Climactic Data Center; NCDC) (n=6). Data were provided hourly from NCDC and in 15 minute intervals from Delaware Coastal Programs. The numbers of days with a maximum gust or a maximum hourly average speed greater than 10 meter per second (mps) or greater than 15 mps were examined for spatial trends.

Sediment Contamination

Sediment contamination data were provided by NOAA (NOAA 2001) from sample stations throughout the bay and river, with the exception of the East Stroudsburg, PA area. The data was collected as part of an evaluation of the sediment contamination and toxicity in the Delaware Bay estuary and contiguous areas as part of the National Status and Trends Program. Samples (n = 81) were collected in July-September, 1997,

between the fall line (just north of the Philadelphia, Pennsylvania city limits) to the coastal area beyond the mouth of the bay, using a stratified random design (see NOAA 2001 for detailed methods). Because of the lack of any sediment data points near the East Stroudsburg area nests, they were removed from the subsequent analyses. All concentrations of organic contaminants (hexachlorobenzene, α -HCH, γ -HCH, heptachlor, heptachlor epoxide, oxychlordane, α -chlordane, γ -chlordane, *cis*-nonachlor, *trans*-nonachlor, aldrin, dieldrin, endrin, mirex, endosulfan II, and DDT and metabolites) were added together within each site, to provide an estimate of the total sediment contaminant load. The sum of the organic contaminants was log transformed to meet assumptions of normality. The data were analyzed for trends and linear regression was used to interpolate data for the study area, with latitude and longitude as independent variables and no intercept. Average total sediment contaminant loads within 3 km of nests sites were calculated.

Air Pollution

Air pollution was estimated from the U.S. Environmental Protection Agency's (USEPA) Aerometric Information Retrieval system (AIRs; <http://www.epa.gov/air/data/aqsdb.html>) data. Hourly mean concentrations of criteria pollutants in air were obtained from the AIRs database. All air pollution data were converted to a common unit (parts per million; ppm). Weekly maximum concentrations of several criteria pollutants (sulfur dioxide, ozone, particulate matter, and lead) from stations within 20 km of the Delaware/Pennsylvania coast of the river and bay were examined for presence of spatial trends during Julian weeks 19 to 22 of 2002 (early nestling period). Particulate matter (PM 2.5), sulfur dioxide, and ozone were

interpolated with linear regression (General Linear Models, SAS V8). Mean sulfur dioxide, ozone, and particulate matter were calculated within 3 km around each nest site.

Distance to Active Osprey Nest

The Euclidean distance (straight-line distance; m) of each inactive nest to the closest active nest was measured by a spatial join (ArcView 8.2, ESRI). For active sites, the Euclidean distance to the next closest active nest was measured using ET Geowizards 8.2 point distance tool (www.Ian-ko.com 2002). Measurements were made in NAD83 Zone 18 UTM projection.

Distance to Water

The Euclidean distance (m) to water was measured as the distance of a nest to the nearest part of the MDN GAP land use coverage classified as water, using a spatial join (ArcView 8.2, ESRI). Measurements were made in NAD83 Zone 18 UTM projection.

Organic Contaminant Exposure

Sample eggs from 39 nests in the Delaware River and Bay were chemically analyzed; detailed analytical methods and results are reported elsewhere (Toschik et al. in preparation; see Chapter 2). Total PCBs, chlordane and metabolites, heptachlor epoxide, *p,p'*-DDE, and dioxin toxic equivalents (a weighted average of the most toxic PCB congeners; TEQs) were considered for the productivity model because they were found in highest concentrations relative to their known toxicity. Contaminant concentrations were tested for homogeneity of variance and log transformed to stabilize variances.

Contaminant concentrations in eggs were strongly correlated; a principal components analysis (PCA) was utilized to clarify their effects. The TEQs were not individually correlated with egg hatching success, unlike the other four contaminant variables; PCA

was run including TEQs and without TEQs. The PCA without TEQs revealed that 91.8% of the total variance was explained by the first principal component, and the four contaminants included in the analysis were weighted almost equally within the first component. Therefore, the first component was retained for use in the hatching success model. The PCA including TEQs performed only slightly better, so TEQs were not included in the final model.

Methods for Evaluating Osprey Habitat Suitability: Logistic Regression Model Development

A logistic regression model for osprey nest activity was developed using the variables described above. Potential explanatory variables (n = 16; Table 6) first were examined individually to determine if they exhibited spatial variability. Variables that did not exhibit spatial variability were not included in the logistic regression models. Model selection was done using the all possible models approach (SAS Institute, Inc., Cary, NC). Candidate models for further exploration were determined for nest activity based on model Chi-square values, and several models containing 3 to 5 variables were examined further. The Δ AIC, Pearson goodness of fit, R-square, percent concordant, false positives and negative identifications, and the Hosmer-Lemeshow lack of fit were examined to further narrow down the candidate “best” models. Final model selection was based both on the above review and the expected ease of access to similar data or expense of collecting similar data in other regions.

A map of predicted osprey habitat use was created by sampling water clarity, water depth, urban land use, and distance to active nest data layers at points 0.005 degrees (\approx 430 m) apart over the study area. The data from this sampling were used in

Table 6. Variables examined in the osprey habitat and productivity models

Variable	Delaware Nest Activity Model	Delaware Hatching Success Model	HSI Vana- Miller 1987	Gulf of Maine Banner and Schaller 2001
Distance to Active Nest	+			+
Distance to Water	+			+
Fish Biomass	+	+	+	
Lead Air Pollution	+	+		
Ozone Air Pollution	+	+		
Particulate Matter Air Pollution	+	+		
Percent of Agricultural Land Use		+		
Percent of Marsh Land Cover		+		
Percent of Shrub Land Cover		+		
Percent of Urban Land Use		+	+	
Percent of Water Land Cover		+		
Presence of Agricultural Land Use	+			+
Presence of Marsh Land Cover	+			+
Presence of Shrub Land Cover	+			+
Presence of Urban Land Use	+			+
Presence of Water Land Cover	+			+
Principle Component 1		+		
Sulfur Dioxide Air Pollution	+	+		
Total Sediment Organic Contaminants	+			
Water Clarity	+		+	
Water Depth	+			+
Wind Speed	+			

*Variables retained in the final model

the final logistic regression model to obtain a map of predicted probabilities for osprey nest activity. Predictive capability north of the Delaware State border was limited due to data gaps in this area, so figures only display data for Delaware State.

Methods for Comparing Model to the Existing Models

The Habitat Suitability Index (HSI) model (Vana-Miller 1987) uses the following

five parameters to estimate overall habitat suitability:

- a. Fish standing crop (usually obtained from transects by fisheries biologists)
- b. Water surface obstruction (obtained from transect or aerial images)
- c. Mean water transparency (obtained from transects with secchi disk)
- d. Human activity (transect or aerial images)
- e. Number of potential nesting structures (census)

Variables *a* through *e* were used in the lacustrine model, and variables *b* through *d* were used in the riverine model. The same data layers described above were used to calculate the average riverine HSI score for a 0.2 km buffer around each osprey nest (active and inactive), with a few minor changes. Vana-Miller estimated human activity by the type and frequency of disturbance within 0.5 km of the nest, with low frequency disturbance and disturbance initiated during the late breeding season scoring as the worst habitat, and continuous disturbance scoring as the best habitat. In the current study, human activity was evaluated based on the percent of urban land use within a 0.2 km buffer around the nest, and only “constant” disturbance could be accounted for. This method of estimating human disturbance was reasonable, because the percent of land use defined as urban in the nest buffers gave a human disturbance score within the range of values for “constant” disturbance. The Atlantic Coast of the U.S. is heavily industrialized and densely populated, so it is reasonable to assume that where disturbance along the coast occurs, it is relatively constant temporally. The classification of “occasional” disturbance is more applicable to the large public lands in the western U.S., where it is actually possible to have no human contact with a breeding osprey during the first few

months of the breeding season. The secchi disk depth was scored as described in the original HSI document, on a scale of 0 to 1, with 1 being the clearest. Water surface obstruction was assigned a score of 1 for all nests, because the landscape around the Delaware River and Bay does not have obstructions normally found on smaller rivers. A logistic regression model was then run using HSI score as the explanatory variable. To address the possible concern regarding the assignment of a single water surface obstruction score to all nests, the model was evaluated with a variety of alternative scores. We found that the HSI model was robust to changes in the water surface obstruction score, and therefore it was appropriate to assign a single score to all nests.

The Gulf of Maine model (Banner and Schaller, 2000) used land use, proximity to water, water depth, and proximity to active nests to predict habitat suitability. Scrub habitat was identified as the preferred land use for ospreys in the Gulf of Maine (Banner pers. comm.), so we ran the model with all land use types (water, marsh, scrub, urban, agriculture), as well as with a scrub habitat indicator only. The results were compared to the other models.

Methods for Evaluation of Osprey Productivity – Logistic Regression Model

A subset of 39 nests for which we had detailed productivity data and contaminant data from egg contents was used to develop a model for osprey productivity. The model was initially developed using only contaminant concentrations as independent variables (Toschik et al. in prep.); this paper examined habitat variables in conjunction with the contaminant variables to determine if other habitat variables also affected productivity. All variables (n = 11; Table 6) for the productivity model described above were included in the model, with several changes. The land use and land cover were summarized as a

percent of the buffer area, rather than being classified as present or absent.

Organochlorine contaminants in eggs were included in the model (PCBs, chlordane and metabolites, heptachlor epoxide, and *p,p'*-DDE). Because the organochlorine contaminants were correlated, a principal components analysis was used to clarify their effects. The first principal component explained 91.8 % of the total variation; in this component the eigenvectors indicated that the four contaminant groups were almost equally weighted. The response variables were fledgling success and hatching success. The optimum number of variables was determined (n = 1 to 3) based on model Chi-square values, and several models with this number of variables were examined further. The same model selection procedure used for the nest activity model was employed to select the most appropriate productivity model.

RESULTS

Evaluation of Osprey Habitat Suitability – Individual Parameters

Water Clarity

The mean secchi disk depth was 0.68 ± 0.022 (mean \pm SE) in buffers around active nests, 0.55 ± 0.019 around inactive nests, and 0.57 ± 0.016 for random points. Average HSI score (Vana-Miller 1987) for water clarity in buffers around active nests was 0.670 ± 0.012 ; for inactive potential nest sites it was 0.626 ± 0.012 ; and for random points it was 0.616 ± 0.010 .

Nest Availability

Available nests were distributed unequally in the study area, with most available nests found around 38.6 and 39.8° N latitude (Figure 6a). However, the distribution of active nests was strongly skewed to the north, with the most active nests found around

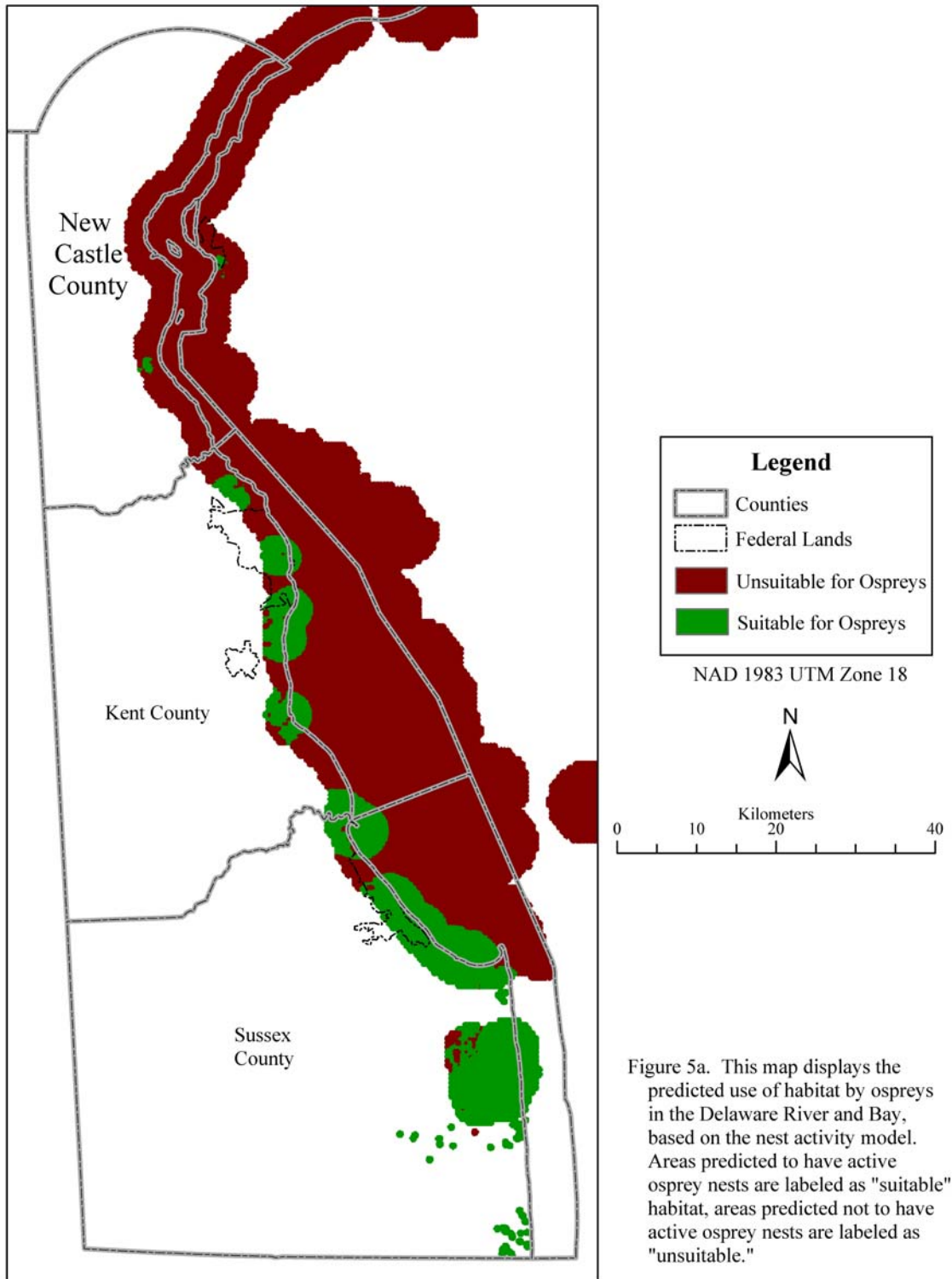
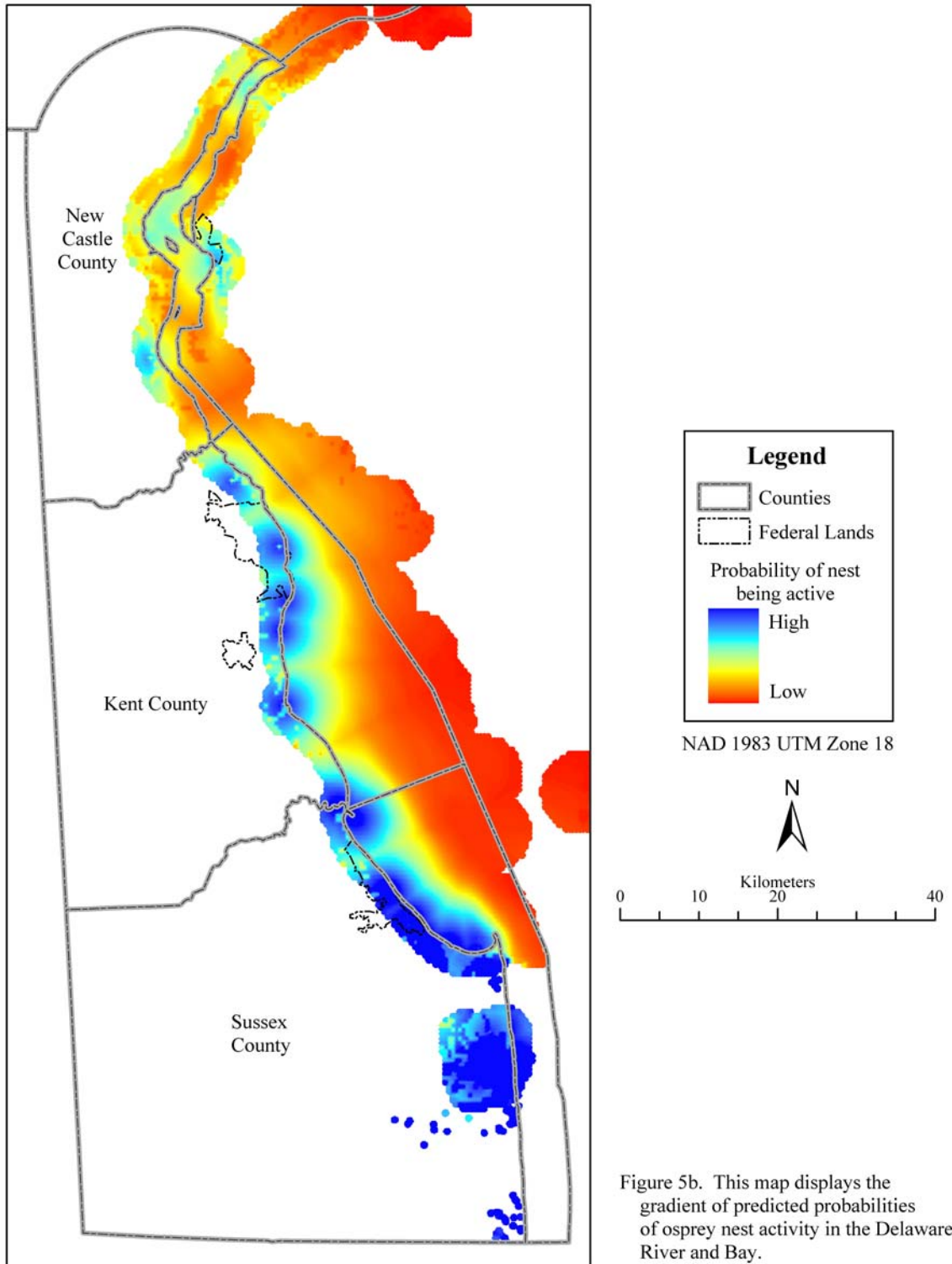


Figure 5a. This map displays the predicted use of habitat by ospreys in the Delaware River and Bay, based on the nest activity model. Areas predicted to have active osprey nests are labeled as "suitable" habitat, areas predicted not to have active osprey nests are labeled as "unsuitable."



38.6° N latitude (Figure 6b).

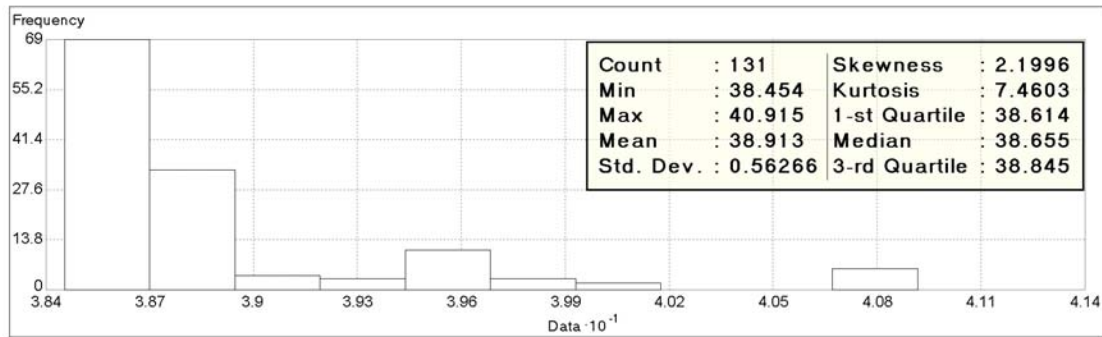


Figure 6a. Latitude vs. frequency of active osprey nests

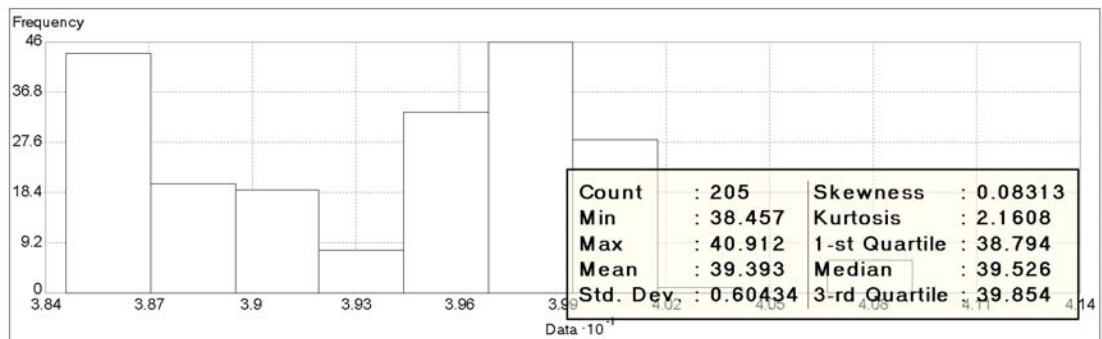


Figure 6b. Latitude vs. frequency of inactive osprey nests

Water Depth

Of 131 buffers around active nests, 50 did not contain water for which we had depth data; the remaining 81 buffers had 298 or more depth points. Depth of water within 3 km of active nests was 2.0 ± 0.145 m; the mean minimum depth within a buffer was 0.5 m; the mean maximum depth within a buffer was 6.6 m. Of 205 inactive nest structures, 68 did not have any depth measurements in their buffer and 137 had 254 or more depth points. Mean depth of water within 3 km of inactive nests was 4.2 ± 0.194 m; mean minimum depth was 0.5 m; mean maximum depth was 11.0 m. Of 417 buffers around random points, 229 did not contain water for which we had depth data and 118 buffers had 10 to 31,390 depth points. Mean depth of water within 3 km of random

points (mean \pm SE) was 5.3 ± 0.317 m; the mean minimum depth within a buffer was 0.2 m; the mean maximum depth within a buffer was 11.5 m.

Land Use and Land Cover

Table 7 contains the LULC map classes that were found within at least 1 buffer area. Initial data showed that osprey apparently preferred to nest over water, coastal marshes or shrubs, and avoided agricultural and urban areas. Active, inactive and random sites displayed different frequencies of occurrences of the “lumped” LULC classes ($p < 0.05$, Chi-square test of independence; Table 8).

Table 7. Occurrence of sample points within LULC map classes.

Map Code	Map Class	Active	Inactive	Random
400	water	+	+	+
401	tidal shallow/turbid			
402	row crops	+	+	+
403	tidal herbaceous beach community	+	+	+
404	tidal high marsh	+	+	+
405	tidal marsh	+	+	+
406	tidal tallgrass marsh	+	+	+
407	lowland pine woodland	+	+	+
408	mixed grass/low shrubs	+	+	+
409	tidal maritime shrublands	+	+	+
410	coastal lowland pine forest			
411	coastal upland pine forest	+	+	+
412	nontidal flooded herbaceous	+	+	+
413	bare sand	+	+	+
414	cultivated trees	+	+	+
415	loblolly - mixed oak forest		+	+
416	Virginia pine forest			
417	Virginia pine - mixed oak forest			+
418	coastal plain pine - mixed hardwood lowland forest	+	+	+
419	sweetgum swamp		+	+
420	mixed wet oak forest			
421	coastal plain beech - oak forest	+	+	+
422	yellow poplar forest			
423	sweetgum forest	+		+
424	sycamore-mixed hardwood riverside forest		+	+

425	red maple - pumpkin ash swamp			+
426	bald cypress tidal swamp		+	+
427	urban	+	+	+
428	lowland mixed oak forest	+		+
429	bare/exposed/manmade features	+	+	+
430	clearcut/transitional	+	+	+
431	beachgrass shrublands			
432	dwarf beach shrublands	+	+	+
433	tidal cattail marsh	+	+	+
434	mixed pines forest			+
435	red pine forest			+
436	red oak - white oak forest	+	+	+
437	nontidal sparsely vegetated beach alliances	+	+	+
438	chestnut oak forest			+
439	beech - yellow poplar forest			
440	high mountain shrub swamp			
441	mixed oak - sugar maple forest	+	+	+
442	rich northern hardwood forest	+	+	+
443	freshwater tidal emergent marsh		+	+
444	redcedar woodland			+
445	piedmont beech - oak forest		+	+
446	tidal atlantic white-cedar forest			
447	shortneedled pine-mixed dry oak forest (pine barrens)			+
448	pitch pine wet woodland			
449	highbush blueberry - leatherleaf shrub swamp			
450	inland graminoid marsh		+	+
451	hemlock - mixed hardwood forest			+
452	urban recreational grasses		+	+
453	pasture/hay	+	+	+
454	dune grassland	+	+	+
455	nontidal tallgrass marsh	+	+	+
456	nontidal mixed grass/low shrub	+	+	+
457	nontidal maritime shrublands	+	+	+
458	red maple - green ash swamp			+
459	nontidal mixed hardwood - conifer swamp		+	+
460	nontidal cattail marsh		+	
461	nontidal atlantic white-cedar forest			

Table 8. Percent of 0.2 kilometer buffers containing lumped LULC map classes.

Map Class	Active	Inactive	Random
Agriculture	15.4	14.6	41.0
Coastal Marshes	60.0	35.6	14.4
Shrubs	19.2	8.3	6.0
Urban	16.9	31.7	29.0
Water	91.5	88.3	45.1

Fish Biomass

Fish biomass was negatively correlated with presence of active nests. This unexpected relationship is possibly indicative of interactions between osprey nest site selection and fish

habitat preference or other habitat factors, such as water clarity and depth. While the osprey was more often found near clear, shallow water, the greatest fish biomasses were located in areas with less clear, deeper water. It is also possible that the spatial distribution of the biomass sampling led to a seemingly paradoxical result. The sampling largely took place off shore and it is probably incorrect to interpolate the fish biomass results from the main stem of the bay into the more shallow areas. More research needs to be performed before a definitive answer is possible.

Wind Speed

The number of days with a maximum gust or a maximum hourly average speed greater than 10 mps or greater than 15 mps showed no spatial variability, so wind speed was not included in the logistic regression model. Data from additional stations could possibly elucidate spatial trends if they are present, but these data were not available or do not exist for the study region.

Sediment Contamination

Sediment organics were significantly correlated with all other variables in the nest

activity model (Pearson correlation, $p \leq 0.0001$). The data exhibited both latitudinal (R-square 0.672, $p < 0.0001$) longitudinal (R-square 0.128, $p < 0.0007$) trends.

Air Pollution

Particulate matter did not exhibit spatial trends and so was not used in further analyses. There was insufficient lead data available for the months of interest (March – August), and so this parameter was not included in the model. Ozone and sulfur dioxide were strongly correlated with other variables in the logistic regression models. When they were included in the productivity model selection procedure, they were often in models with the highest Chi-square value for each number of variables. However, replacement of these air pollution parameters with other parameters did not change the Chi-square score for the model greatly. This probably indicates that ozone and sulfur dioxide, and the variables they were interchangeable with, (e.g., sediment contaminants, water depth, presence of urban land use) are all indicators of some general disturbance variable that affects an osprey's decision to use a nest site.

Organochlorine Contaminant Exposure

The first principal component explained over 90% of the variability, and so was retained for the logistic regression model. The first component was almost equally representative of total PCBs, *p,p'*-DDE, chlordane and metabolites, and heptachlor epoxide.

Evaluation of Osprey Habitat Suitability – Logistic Regression Model Performance

Several different models were identified as candidates for the osprey habitat suitability model (Table 9). The model selected as the overall 'best model' to predict osprey nest activity uses presence or absence of urban land use, water clarity, water

Table 9. Subset of models examined for predicting osprey nest activity

# of Variables	Variables	Chi ²	ΔAIC	Deviance/ Pearson	R ²	% Concordant	False +	False -	% Correct	Lack of Fit	P
2	sediment organics, distance to active nest	78.9	92.3	.06/.5	0.345	78.6	36.1	17.7	74.1	0.50	0.54
2	ozone, distance to active nest	78.6	93.1	0.06/0.47	0.349	78.7	36.9	15.8	74.1	0.57	0.50
2	water depth, sediment organics	78.5	72.6	.04/.49	0.283	74.9	40.7	15.4	71.3	0.34	0.40
3	water depth, sediment organics, distance to active nest	82.6	102.7	.10/.799	0.371	78.4	39.1	19.2	71.6	0.29	0.54
3	water depth, ozone, distance to active nest	82.2	102.4	.105/.772	0.371	78.3	38.3	19	72.3	0.13	0.54
3	ozone, distance to water, distance to active nest	82.1	95.7	.09/.53	0.361	79.3	36.4	18.9	73.5	0.67	0.48
4	water depth, marsh, sediment organics, distance to active nest	85.0	102.0	.11/.798	0.375	78.5	39.2	17.1	71	0.35	0.54
4	water depth, urban, ozone, distance to active nest	84.5	108.5	.239/.934	0.373	78.9	40.1	21	69.7	0.52	0.50
4	water depth, sediment organics, distance to water, distance to active nest	84.4	101.4	.106/.764	0.366	78.5	40	19.1	71	0.82	0.52
4	water depth, water clarity, urban, distance to active nest	86.3	107.6	.23/.896	0.385	79.1	39.3	21.8	70.7	0.44	0.52
5	water depth, marsh, sediment organics, distance to water, distance to active nest	87.0	100.7	.116/.784	0.379	79	38.6	21.3	71.3	0.40	0.54
5	water depth, urban, marsh, sediment organics, distance to active nest	86.9	107.7	.23/.93	0.381	78.8	35.2	25.5	71.3	0.09	0.60
GOM	water depth, urban, marsh, ag, shrub, water, distance to active nest, distance to water	82.1	107.4	.255/.959	0.399	78.6	41.6	27.9	67.4	0.43	0.56

depth, and distance to nearest active nest. The parameter estimates for the variables in this model are shown in Table 10. The classification table (Table 11) is useful for evaluating the fit of a model and determining what constitutes a reasonable cutoff value for predicting presence or absence of breeding ospreys at a potential nest site. The classification table for the nest activity model indicated that the probability cut-off for nest activity predictions should be set at 0.5. Figure 5 shows maps of osprey habitat quality and areas that the model predicts will have active nests ($p \geq 0.5$) or inactive nests ($p < 0.5$). These maps should be updated periodically as land use maps and other variables are updated to reflect changes in the habitat.

Based on the most up to date information used in this study, all habitat within the state of Pennsylvania and Kent County, Delaware, was classified as “unsuitable for

Table 10. Parameter estimates for significant* variables in the Delaware Habitat

Parameter	Maximum Likelihood Estimate	Standard Error	Chi-Square	P	Point Estimate	LCL	UCL
Distance to Active Nest	-0.22	0.05	17.06	<.0001	0.81	0.73	0.89
Presence or Absence of Urban Land Use	-0.58	0.31	3.54	0.06	0.56	0.30	1.03
Water Clarity	1.24	0.58	4.60	0.03	3.45	1.11	10.70
Water Depth	0.14	0.07	3.34	0.07	1.15	0.99	1.33

*Significance = $p < 0.1$

ospreys,” with a few small exceptions. In Pennsylvania, a small area near Neshaminy State Park and a small area near East Stroudsburg were identified as “suitable” habitat. In New Castle County, Delaware, a small area crossing over the border into Supawna Meadows National Wildlife Refuge in New Jersey, and another small area near the mouth of the Appoquinamink River and Augustine Wildlife Area were identified as “suitable” habitat. In Kent and Sussex counties in Delaware large patches of “suitable” osprey habitat were identified. When compared to the actual active nest distribution, much of the habitat in Sussex County is in use by ospreys, while few active nests were found in Kent County.

Comparison of HSI models

The USFWS HSI model developed entirely from literature information and expert knowledge performed very poorly (Table 12) for the Delaware Bay. The Gulf of Maine model (Table 12), originally fit to real locations of osprey nests, performed similarly to the models described in Table 9. The only detriment to Gulf of Maine model was the

Table 11. Classification table for osprey nest activity model

Probability Level	<u>Correct</u>		<u>Incorrect</u>		% Correct	Sensitivity	Specificity	False +	False -
	Event	Non-Event	Event	Non-Event					
0.20	121	102	100	5	68.0	96.0	50.5	45.2	4.7
0.24	118	107	95	8	68.6	93.7	53.0	44.6	7.0
0.28	112	111	91	14	68.0	88.9	55.0	44.8	11.2
0.32	111	116	86	15	69.2	88.1	57.4	43.7	11.5
0.36	106	121	81	20	69.2	84.1	59.9	43.3	14.2
0.40	103	128	74	23	70.4	81.7	63.4	41.8	15.2
0.44	94	133	69	32	69.2	74.6	65.8	42.3	19.4
0.48	90	139	63	36	69.8	71.4	68.8	41.2	20.6
0.52	85	147	55	41	70.7	67.5	72.8	39.3	21.8
0.56	77	151	51	49	69.5	61.1	74.8	39.8	24.5
0.60	67	162	40	59	69.8	53.2	80.2	37.4	26.7
0.64	50	175	27	76	68.6	39.7	86.6	35.1	30.3

slightly lower predictive capabilities compared to the Delaware Bay model derived herein. However, all variables used were relatively simple, inexpensive variables to collect, and the existing data are likely to be available for most locations. The comparability of the Gulf model to the Delaware model is remarkable, and is an indication that habitat requirements for ospreys are similar over a broad region.

Evaluation of Osprey Productivity – Logistic Regression Model Performance

Table 12. Comparison of model statistics

Model	# of Variables	Variables	Chi-Square	Δ AIC	R^2	% Concordant	False +	False -	% Correct	Lack of Fit	P	# of Significant Variables
Delaware Habitat Suitability	4	water depth, water clarity, urban, distance to active nest	83.8	107.6	0.385	79.1	39.3	21.8	70.7	0.435	0.52	4
Gulf of Maine	4	water depth, shrub, distance to active nest, distance to water	74.5	95.3	0.360	77.1	42.3	18.1	69.5	0.137	0.48	2
USFWS HSI	1	riverine hsi score	8.9	6.7	0.036	59.8	49.5	24.5	61.9	0.003	0.40	1
Nest Activity	1	principal component 1	6.1	3.6	0.104	64.5	41.7	20.0	77.0	0.205	0.40	1

“Productivity” was defined as hatching success, because fledging success did not exhibit any trends. Initial model selection procedures indicated that the principal component, percent of urban land use, water clarity, and percent of water could be useful in predicting productivity. However, the best model for osprey productivity was the model using only the principal component, representing total PCBs, *p,p'*-DDE, chlordane and metabolites, and heptachlor epoxide. While the model fit and predictive capabilities were good, the productivity model did not perform quite as well as the habitat model (Table 12); however, it is still a useful model for obtaining a rough estimate of osprey hatching success at active nests.

DISCUSSION

Relative Importance of Contaminants and Other Habitat Factors

While the logistic regression model including sediment contaminants as an explanatory variable performed as well as several other nest activity models, it was not included in the final model for several reasons. One of the primary goals of this research

was to provide a cost-effective model for osprey habitat suitability and the costs become prohibitive in areas where the data would need to be collected as part of the habitat evaluation. In addition, sediment contaminants were correlated with most other variables in the model, making it difficult to separate their effects on osprey habitat use from the effects of other parameters in the model.

However, the cost of analysis of contaminants in osprey eggs is apparently warranted in conjunction with an evaluation of hatching success. The principal component (contaminants) provided a better predictor of productivity than any other habitat parameters considered in this study. It is remarkable that organochlorine contaminant exposure still shows effects on egg hatching. The contaminants may be a general indicator of stress from human impacts on the birds and their habitat, because it is unlikely that it is from the extensive eggshell thinning seen during the era of DDT use.

While a relationship between nest locations and wind speed was expected, the limited amount of available data prevented elucidation of this potential relationship. The relationship of osprey nest activity to water clarity could become far more relevant for conservation efforts if conditions in the bay area worsen. Plans to dredge Delaware Bay (ACOE 1996) could produce water clarity issues significant to ospreys and possibly other piscivorous birds on the bay. Nutrient issues in the Inland Bays could challenge the osprey population there if water clarity is further affected. Hypotheses regarding food limitation may be best left to egg switching experiments when there is reasonable evidence of limitation at a specific site (Spitzer 1978), as fish biomass is generally expensive to collect and available data indicate that food is not a limiting resource for ospreys in the Delaware Bay.

Management Implications

A common concern with avian habitat models is the source of the data – generally the models are based on expert information and not fit to actual data or tested in the field (Dettmers et al. 2002). While confidence in the performance of these models is low, they are often the only resource for wildlife managers (Dettmers et al. 2002). When a set of 25 models for songbird habitat use were field tested, between 48 and 77% of the models performed poorly, depending on the sampling location and species behavior (Dettmers et al. 2002). In contrast, logistic regression models utilizing presence/absence data perform quite well, and can actually provide a suitable surrogate for abundance models for some species (Pearce and Ferrier 2001).

Several models for osprey habitat were presented in this paper to allow habitat managers to select the best model for their region, based on data available to them. The current status of osprey populations in the United States justifies the cost of aerial nest surveys and water clarity measurements with a secchi disk, but not extensive or costly data collection (i.e. creating a detailed land use map, measuring water depth over hundreds of km, or conducting intensive sediment contaminant surveys). Use of these models should be based on the best model for which data can be obtained, and its application should be iterative, updating the base data as the environment changes. Future platform installations should be limited to areas near clear, shallow water, more than 0.2 km from urban areas, and away from sites where greatest contaminant concentrations were found in the 2002 egg collections. Current data for Delaware suggest it is not advisable to encourage osprey nesting on the river and bay north of the Bombay Hook/Port Mahon area without also undertaking habitat improvement measures.

Base data should be updated at regular intervals to focus resources accurately. And possibly most important, HSI models developed solely from literature and expert opinion are useful bases for modeling habitat suitability, but they need to be fit to field data before use (see also Dettmers et al. 2002; Pearce and Ferrier 2001). The models developed in the present study should be tested at other locations in order to verify their applicability over a national or international scale.

CHAPTER 4: CONCLUSIONS

Despite the contaminant concentrations being below thresholds known to affect productivity in ospreys, the contaminant-based principle components provided the best predictors of productivity compared to other habitat parameters considered in this study. Logistic regression models of reproductive success indicated that concentrations of *p,p'*-DDE, chlordane and metabolites, heptachlor epoxide, and total PCBs (rather than habitat factors) were predictive ($p < 0.05$) of hatching success, but not fledging success. It is remarkable that organic contaminant exposure continues to show effects on egg hatching. These contaminants may represent a more generalized stressor on the birds and their habitat; the extensive eggshell thinning seen during the era of DDT use has diminished. Concentrations of *p,p'*-DDE, Dieldrin, oxychlordane, total PCBs, TEQs, PBDEs, and mercury in osprey eggs from the Delaware River and Bay were quite similar to average values found in osprey eggs from Chesapeake Bay regions of concern (Rattner et al. in press). Presence and concentration of perfluorinated acids compounds were slightly higher in the Delaware River and Bay eggs than in those collected in the Chesapeake Bay.

The productivity for all regions was within or above the range estimated to maintain a population for ospreys on the east coast of the U.S. (0.8 – 1.15; Poole 1989), although productivity in the northern and riverine segments was lowest at 1 fledgling/active nest. Productivity was generally greater than in 1989 (< 0.8 fledglings/active nest; Steidl 1991a), and productivity in the south and central segments was similar to 1994-1998 productivity for ospreys in the Salem and Maurice River areas of New Jersey (1.1 fledglings/active nest; Clark et al. 2001). The Delaware Bay is 1/5th

size of the Chesapeake Bay, but has 1/50th the number of nesting ospreys, probably due to differences in water depth and clarity.

OUTLOOK

The relationship of osprey nest activity to water clarity could become far more relevant for conservation efforts if conditions in the bay area worsen. Plans to dredge the bay (ACOE 1996) could produce water clarity issues significant to ospreys and probably other piscivorous birds on the bay. Nutrient issues in the Inland Bays could challenge the osprey population there if water clarity is further affected.

In 1975 only 5 pairs of osprey were found breeding between Wilmington Bridge south to Cape Henlopen, Delaware (Henny et al. 1977), an area that contained at least 45 active nests in 2002. However, recovery of the osprey population as a whole in the Delaware Bay is still incomplete. For example, 6 active nests were observed in Kent County in 2002, still well below the historical 90 nests observed in the same region prior to the widespread use of organochlorine pesticides, even though more than 30 years have elapsed since their use was discontinued (Hess et al. 2000). Assuming the management goal for this species is to have the population return to near historic levels, there is much left to be accomplished in restoring their habitat beyond the Inland Bays region.

MANAGEMENT RECOMMENDATIONS AND RESEARCH NEEDS

Several models for osprey habitat were presented in this paper to allow habitat managers to select the best model for their region, based on data most accessible to them. The current status of osprey populations in the United States justifies the cost of aerial nest surveys and water clarity measurements with a secchi disk, but not extensive or costly data collection (i.e. creating a detailed land use map, measuring water depth over

100s of km, or conducting intensive sediment contaminant surveys). Use of these models should be based on the best model for which data can be obtained, and its application should be iterative, updating the base data as the environment changes. Future platform installations should be limited to areas near clear, shallow water, more than 0.2 km from urban areas, and away from sites where greatest contaminant concentrations were found in the 2002 egg collections. Base data should be updated at regular intervals to focus resources accurately. Current data for Delaware suggest it is inadvisable to encourage osprey nesting on the river and bay north of the Bombay Hook/Port Mahon area without also undertaking habitat improvement measures. Moreover, HSI models developed from solely literature and expert opinion are useful bases for modeling habitat suitability, but they need to be fit to field data before use (see also Dettmers et al. 2002; Pearce and Ferrier 2001). The models developed in the present study should be validated at other locations in order to verify its applicability over a national or international scale.

Perfluorinated compounds and polybrominated diphenyl ethers did not have significant effects on fledglings produced per active nest, though the patterns in some of the data (esp. perfluorodecanesulfonate, perfluorodecanoic acid, perfluorononanoic acid, and perfluorooctanesulfonate) indicate this might be worth further research with a larger sample size (Figure 3 a,b). Little is known about the direct and indirect effects of these compounds on wildlife, despite evidence that diverse wildlife species are exposed to these compounds around the world (Kannan et al. 2001; 2002a,b; Rattner et al. in press; de Witt 2002). This is certainly an area that would benefit from controlled laboratory and field experiments.

CLOSING REMARKS

While the outlook for ospreys in Delaware River and Bay is quite good, the population is still facing challenges in its recovery from the past population decline. Concentrations of many chemicals in the osprey eggs have decreased in the last few decades (e.g., *p,p'*-DDE); however, human impacts on this population are still measurable, and chemicals known to be harmful to laboratory animals are consistently being detected in the osprey eggs. Further research to develop adverse effect concentrations of perfluorinated chemicals and polybrominated diphenyl ethers in birds should be a priority for use in this region and other urban wildlife habitats. A decline in habitat quality factors (e.g., water clarity) in the Delaware River and Bay could put even greater stress on the population, which is already struggling in the central and northern portions of this region. This is a realizable risk with potential dredging activity in the main shipping channel. Future monitoring of the nesting activity, breeding success, and contaminant exposure of ospreys throughout the Delaware Bay and River should provide wildlife managers with an indicator of the health of the coastal habitat.

APPENDIX 1: ADDITIONAL BACKGROUND INFORMATION

TRENDS IN CONTAMINANT CONCENTRATIONS

Recent studies of osprey in the nearby Chesapeake Bay indicate contaminant concentrations below the threshold expected to affect productivity (Rattner et al. in press). However, ospreys nesting in historically contaminated sites were at lower densities than those at the reference site (Rattner et al. in press). One explanation for this is that the habitat quality and contaminant concentrations have combined sublethal effects.

Eggshell thinning as a result of exposure to the pesticide metabolite *p,p'*-DDE caused catastrophic declines in several species of birds, notably the bald eagle, peregrine falcon, and osprey. Lead poisoning in waterfowl may have been the major cause of mortality for several decades, before the introduction of non-toxic shot. Chlordane poisoning continues to be a cause of mortality for passerines and raptors (see for example NYDEC 2001) even though most uses of chlordane were banned decades ago. This sensitivity to contaminants makes birds useful indicators of ecosystem health.

While concentrations of *p,p'*-DDE in osprey eggs have generally fallen in the past 20 years, PCB concentrations have not declined as rapidly (Wiemeyer et al. 1978; Rattner et al. in press). The PCB concentrations in osprey eggs sampled from nests in the Chesapeake Bay in 2000 and 2001 were elevated (up to 17 µg/g), although they were not high enough to cause measurable reproductive effects (Rattner et al. in press).

COMPETITION

Observations made during this study suggest that competition with double-crested cormorants may be an important factor for ospreys in the Delaware River north of the

C&D canal. Others have suggested that competition with bald eagles could affect ospreys, although bald eagles are not as abundant as cormorants and eagles generally no found nesting on channel markers.

PREDATION

Steidl and others (1991) found that predation by great-horned owls is important in Delaware Bay. Due to lack of reliable population estimates for great-horned owls, predation could not be addressed as a factor in this model.

WATER CLARITY AND DEPTH

Ospreys fish by visually searching for fish while hovering or perched, and they are capable of diving a short distance below the surface for prey. This method of fishing requires water that is clear enough to identify possible prey, and shallow enough to prevent prey from escaping capture. Gibbs and co-workers (1991) found that inland ospreys in Maine were associated with wetlands of low pH and conductivity, and therefore, probably clearer water. Ospreys nesting inland in Estonia were found around lakes with an average depth of 3.0 meters, and only foraged within 300 meters of the lakeshore, presumably in the shallowest water (Lohmus 2001).

PROXIMITY TO ACTIVE OSPREY NESTS

Greene (1987) postulated that ospreys nesting in colonies have a reproductive advantage over ospreys nesting individually, because information about fish location can be interpreted from osprey returning to the colony from a successful foraging trip, making provision of food to offspring less energy intensive. However, when other researchers revisited the same colony, they did not find an advantage (increased productivity) of colonial nesting versus individual nesting (Fleming et al. 1991).

WEATHER

Wind speed over 7 m/s decreases osprey foraging efficiency (Machmer and Ydenberg 1989). Wind is of importance because of the limitations of foraging efficiency and because of the susceptibility of osprey nests and nest contents from being blown down in high wind events.

FOOD AVAILABILITY

There is contradictory evidence in past research about the impact of food availability on ospreys. Spitzer (1978) implicates a food shortage in low productivity observed in an osprey colony off the coast of New York, while Steeger and others (1992) found that variability in quality and quantity of food did not affect osprey reproduction. Steeger et al. (1992) suggest that age differences between the osprey populations in their study may have offset the difference in food quality and quantity between the two nesting locations, or that food availability is less important than other factors, such as weather. In eagles, low productivity has been associated with low food availability (Karasov and Meyer 2000). Based on these studies, food availability should not be entirely discounted as a factor in osprey productivity, although other factors must be considered.

NEST SITE AVAILABILITY

Ospreys may benefit from nesting in colonies, as may be the case in Delaware's inland bays, rather than far apart, as is the case in the northern segment of the study area (Greene 1987). Ospreys have been observed to fly in the direction of other ospreys that have returned with a fish, and in the case of schooling fish, they have greater foraging success. The impact of this behavior on productivity has not been confirmed, and it does not occur in all osprey colonies (Green 1987). Watts and co-workers (in press) found that

the increase in nest availability was second only to banning of toxic chemicals, leading to the increase of ospreys in the Chesapeake Bay.

HUMAN DISTURBANCE

Osprey nests in Estonia are all at least 1 km away from human settlement (Lohmus 2001). VanDaele and VanDaele (1981) found that osprey productivity was greater for pairs nesting more than 1500 meters from human activity. Rodgers et al. (2002) found that large waterbirds, including ospreys, flush at greater distances than smaller waterbirds when approached by motorboats and personal watercrafts. They recommend a 150-meter buffer around osprey nests to minimize disturbance (Rodgers et al. 2002). In general, proximity to humans includes proximity to highly contaminated areas (see for example, McCoy et al. 2002; Kannen et al. 2001). In contrast to the aforementioned studies, one study found that human disturbance (quantified by distance from the nest to the nearest road), had no effect on osprey productivity (Gibbs et al. 1991), however, this research was conducted in the sparsely populated state of Maine. My personal observations of ospreys nesting in human inhabited areas suggest that ospreys are only deterred by extreme disturbance such as urban centers with heavy industrialization or intentional and persistent harassing.

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