Research Article

# Evaluation of Osprey Habitat Suitability and Interaction with Contaminant Exposure


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## Abstract

*Ospreys (*Pandion haliaetus*) have been the focus of conservation efforts since their dramatic population decline attributed to dichlorodiphenyltrichloroethane and related chemicals in the 1960s. 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. Because of concerns about pollution in the highly industrialized portions of the Delaware River and Bay, USA, 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, USA, and the area around the river in Pennsylvania, USA, using data we collected as well as extant information provided by state and federal sources. We characterized habitat based on locations of occupied osprey nests in Delaware and Pennsylvania. We evaluated water clarity, water depth, land use and land cover, nest availability, and contaminants in sediment for use in a nest-occupancy model. Our results demonstrated that the presence of occupied nests was associated with water depth, water clarity, distance to an occupied osprey nest, and presence of urban land use, whereas a companion study demonstrated that hatching success was associated with the principal components derived from organochlorine-contaminant concentrations in osprey eggs (total polychlorinated biphenyls,* p,p′-*dichlorodiphenylethylene, chlordane and metabolites, and heptachlor epoxide). Our study provides 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.* (JOURNAL OF WILDLIFE MANAGEMENT 70(4):977–988; 2006)



## Key words

*Delaware Bay, Delaware River, habitat, hatching success, land use, nest density, organochlorine contaminants, osprey,* Pandion haliaetus*, water clarity, water depth.*


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). Delaware Bay is highly industrialized, especially near Philadelphia, Pennsylvania, USA, yet it is also bordered by 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).

Recent studies of ospreys in the nearby Chesapeake Bay indicate organochlorine contaminant concentrations are below the threshold expected to affect productivity (Rattner et al. 2004). However, ospreys nesting in historically contaminated sites were at lower densities than those at the reference site (Rattner et al. 2004). Observations of ospreys breeding in the Delaware River and Bay indicated a similar disparity in osprey nesting density (Toschik et al. 2005). The combination of marginal habitat quality and exposure to environmental contaminants was hypothesized to adversely affect the distribution and breeding success of ospreys among available nesting habitats. Characterizing habitat based on wildlife use provides a tool for population evaluation and management and insight into resource selection (Boyce and McDonald 1999). Numerous techniques for evaluating habitat use have been described and tested (see Alldredge and Ratti 1986, 1992, Bender et al. 1996, Boyce and McDonald 1999).

The primary requirements for a breeding pair of osprey are a safe nest location and access to fish. Safe nest locations are those sites that are protected from human disturbance, competitors (e.g., bald eagles [*Haliaeetus leucocephalus*]), and predators (e.g., raccoons [*Procyon lotor*], great-horned owls [*Bubo virginianus*]; Ewins 1997). Factors such as water clarity and depth (Poole 1989, Dove and Nyman 1995), fish abundance (Spitzer 1978, McLean and Byrd 1991), wind speed (Machmer and Ydenberg 1990), and contaminants in fish (Steidl et al. 1991) can affect access to food and in turn affect the suitability of available nesting habitat. Ospreys have been found to nest in clusters (Lohmus 2001), although they are not considered obligate colonial breeders.

Several studies have addressed effects of individual habitat parameters on ospreys (Spitzer 1978, Levenson and Koplin 1984, Lohmus 2001), yet the combination of contaminant exposure and multiple habitat-suitability factors has not been evaluated. Two methods exist for predicting osprey nest occupancy from environmental variables. The Habitat Suitability Index (HSI) was developed based on osprey life-history literature, and it quantifies habitat quality on lakes and rivers using measures of human activity, water clarity, water-surface obstruction, fish abundance, and the number of potential nesting structures (Vana-Miller 1987). A second method quantifies habitat quality for coastal and estuarine nesting ospreys in the Gulf of Maine (GOM), USA, and it is based on land use, proximity to water, water depth, and proximity to occupied nests (Banner and Schaller 2000). However,


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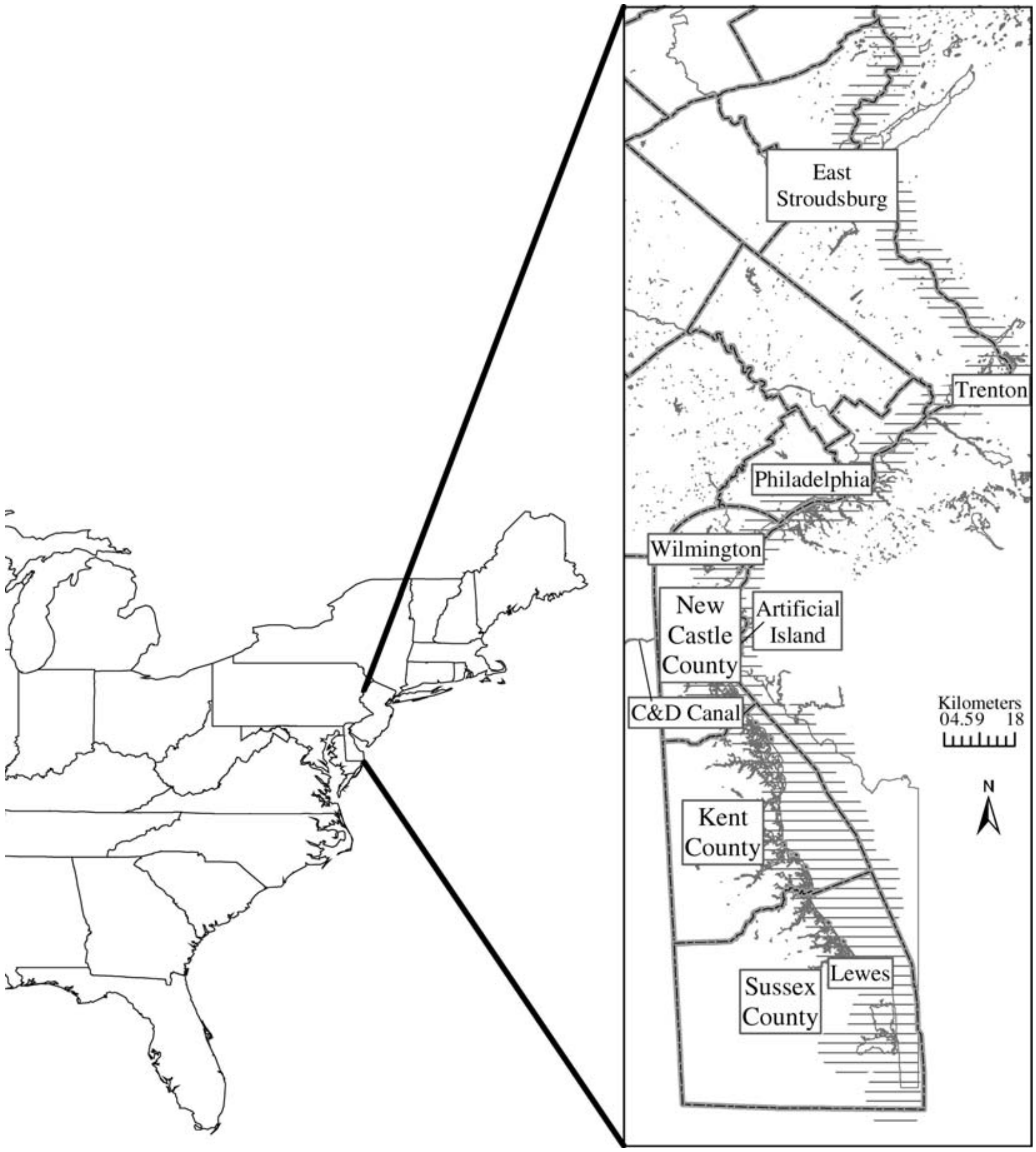


***Figure 1.*** General study area for osprey nesting in the Delaware River and Bay, 2002.

these models are not generally extendable to other areas because the HSI 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 because the primary focus of the GOM study was bald eagle habitat. Neither model addressed other important variables, such as site contamination (e.g., contaminants in sediments); contaminant burdens in eggs, juvenile, or adult ospreys; or productivity of ospreys at occupied nest sites. From a broader estuarine-health perspective, it is well recognized that water quality and local pollution, including chemicals in the water and air, water clarity, nitrogen, and phosphorus, significantly affect habitat quality (Summers 2001).

It is likely that several factors simultaneously affect osprey breeding success in the Delaware River and Bay and elsewhere. Based on a need to better understand osprey habitat requirements to maximize success of management efforts, we evaluated osprey habitat in terms of breeding and success throughout much of the coastal area around the Delaware River and Bay. We used logistic-regression models to predict osprey nest occupancy based on habitat parameters, including environmental contamination. Our objective was to explain the difference in osprey nest density between northern and southern Delaware River and Bay by producing a habitat model for estuarine breeding ospreys based on field data.

## Study Area

We selected the Delaware River and Bay, USA (Fig. 1), 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. This region also provided a unique combination of urban, agricultural, riparian, and coastal marsh habitats, all with breeding ospreys and gradients of other habitat factors of significance to ospreys (contaminant exposure, water depth, water clarity, etc.).

## Methods

### *Methods for Evaluating Osprey Habitat Suitability: Data Preparation*

The parameters we considered for the Delaware River and Bay osprey habitat model included those used in the original HSI model and the GOM habitat model plus several additional parameters. We averaged water clarity, depth, and sediment contaminants in a 3-km buffer around osprey nests because ospreys usually 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. We employed a 0.2-km buffer around the nests for describing land use and land cover variables because proximity of these habitat characteristics to the nest is believed to be important. We generated and analyzed random points in the same manner as the potential and occupied nest locations to determine whether the ospreys were using habitat in a pattern significantly different from a random distribution of nest sites. Potential nest sites (unoccupied nests) were structures that were similar to occupied nest sites (e.g., channel markers and purpose-made nesting platforms).

*Water clarity*.—We collected water clarity data for the Delaware River and Bay and the Inland Bays at 2.5-km intervals approximately 0.5 km offshore of Delaware (secchi disk depth, 20-cm black and white disk, 16–20 Jun 2002). When the substrate was visible from the boat, we used the depth of the water as a surrogate for secchi disk depth. Comparable water clarity data for the river between Trenton, New Jersey, USA, and Artificial Island, New Jersey, USA, were not available, and so we interpolated clarity. We detected a latitudinal trend and latitude–longitude interaction ($P < 0.0001$, analysis of variance [ANOVA]) in secchi disk depth, although we did not find a longitudinal trend. The slope of the line describing water clarity spatial interactions was significantly different above versus below 40° north latitude. Consequently, we divided the data at 40° N latitude and fit them to 2 separate linear regressions. North of 40°, water clarity was related to latitude and longitude ($r^2 = 0.926$, $P < 0.0001$). South of 40°, water clarity was related to latitude, longitude, and the interaction of latitude and longitude ($r^2 = 0.914$, $P < 0.0001$). We interpolated water clarity for the north and south regions, using their respective regression equations to predict the clarity every 0.01 degrees ($\approx$855 m) throughout the study area. We then merged the 2 sets of predicted points 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 (MDN) Gap Analysis Program (GAP) Land Use and Land Cover (LULC) layer and averaged within a 3-km circular buffer around each point or nest site. The method we used to interpolate water clarity would miss any point sources of runoff that could have localized impacts between sites where clarity was actually quantified.

*Nest availability*.—We made efforts to identify all possible occupied and potential nest sites for ospreys in Delaware, USA, and in southeastern Pennsylvania, USA, region bordering the Delaware River and Bay. This included a fixed-wing aircraft survey conducted by the United States Geological Survey (USGS) and United States Fish and Wildlife Service (USFWS) in May 2001, boat and ground searches in 2002, and frequent communication with state and federal agencies and conservation groups. We checked all known nests to determine whether they were occupied 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 (excluding buoys or other unsuitable marker types), and other sites at which occupied osprey nests had been observed between 2000 and 2002.

We recorded locations with a handheld Garmin® Global Positioning System (GPS) 12XL (Olathe, Kansas) in most cases. We estimated several locations from a map based on site information. We plotted nest sites in ArcView® 8.2 (ESRI, Redlands, Washington); several nest location positions required minor manual adjustments based on field observations of the nest site (e.g., a nest on a small island may have been misidentified as over water without the adjustment). We considered nests occupied if they contained eggs or chicks at any time during the 2002 breeding season (1 Apr to 15 Aug). We classified all other sites as unoccupied, potential nest sites. We observed nests at least once during the breeding season, although 2 subsets of nests were monitored more frequently as part of the productivity study (visits at 10-d intervals) and as part of a local osprey-monitoring program (one visit each in spring and in summer). We only included nests within the Delaware and Pennsylvania state borders in our analysis.

*Water depth*.—We acquired bathymetry for the Delaware Bay from the National Oceanic and Atmospheric Administration (NOAA) bathymetry digital-elevation model (DEM; 1998). Bathymetry data for the portion of the river in north Delaware and in Pennsylvania were provided as point data in computer-aided design (CAD) files from the Army Corps of Engineers (ACOE). The precision of the NOAA data layer was sufficient to distinguish 1-m intervals. We converted the DEM to a grid and then converted it to point coverage to permit merging of this data set with the ACOE and Delaware Coastal Programs bathymetry data.

We converted the ACOE data from feet to meters, and we manually georeferenced point files that did not align properly after conversion into shapefiles in ArcView 8.2. Original projection of the data was New Jersey State Plane Federal Information Processing Standard 2900 North American Datum (NAD)83; we converted the data to NAD83 Zone 18 Geographic Coordinate System (GCS) North American to match other data layers. The ACOE and NOAA data set spatially overlapped at the confluence of the river and bay. We analyzed a subset of 500 points from the overlapping area to determine whether the layers aligned properly. We used a linear-regression analysis to do the comparison (ACOE depth $= -2.84 + 0.75 \times$ NOAA depth, $r^2 = 0.623$). Based on this regression, we adjusted the ACOE depths to match the NOAA depths before joining them.

Delaware Coastal Management Programs (DCMP; D. B. Carter, unpublished data) provided bathymetry point data for Rehoboth Bay, Delaware. The original projection of the NOAA and DCMP data layers was NAD27 Zone 18; we converted both layers to NAD83 Zone 18 GCS North American to match other data layers. We then clipped the depth layer to the area defined as "water" on the land use and land cover map.

For all study areas, we buffered potential nest locations and random points to 3 km around each nest site. We calculated average depth from all points that fell within each buffer area.

*Land use and land cover*.—LULC maps were provided by the MDN GAP Analysis Project (2002). The original map had 62 LULC classifications based on 30-m grid cells and was projected in NAD83 Universal Transverse Mercator (UTM) Zone 18. We used a 0.2-km buffer around nest locations and random points for descriptive statistics about local land use at a potential or occupied nesting site. We selected the 0.2-km buffer based on what is believed to be a reasonable distance around a potential nest site to affect an osprey's site selection. Ospreys will nest within 50 to 100 m of other ospreys (Poole 1989), which suggests that the local area of importance around a nest is relatively small. We evaluated the LULC categories within the buffers around each nest using the Pearson chi-square test of independence. For further analysis, we retained those LULC classes that occurred in a greater proportion of occupied than unoccupied nests or those LULC classes that were used in different proportions than were predicted from the unoccupied and random points. Based on this initial evaluation of the data, we simplified subsequent analyses by combining the following 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"; and lowland pine woodland, tidal maritime shrublands, and nontidal maritime shrublands into "shrubs." In addition, we left urban and water in classes by themselves. We excluded all other LULC classes from our analyses because they fell within <5% of the buffers around occupied nests. For the nest-occupancy model, we identified land-use classes as present or absent from the buffers for each occupied and unoccupied nest site. For the hatching-success model, we quantified the percentage of the buffer occupied by each land class.

*Sediment contamination*.—Sediment contaminant data were provided by NOAA (2001) from sample stations throughout the river and bay, with the exception of the East Stroudsburg, Pennsylvania, USA area. Samples ($n = 81$) were collected in July–September 1997, between the fall line (just north of the Philadelphia, Pennsylvania, USA 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, we removed them from the subsequent analyses. To provide an estimate of the total sediment contaminant load, we added all concentrations of organic contaminants (hexachlorobenzene, α-hexachlorocyclohexane [α-HCH], γ-HCH, heptachlor, heptachlor epoxide, oxychlordane, α-chlordane, γ-chlordane, *cis*-nonachlor, *trans*-nonachlor, aldrin, dieldrin, endrin, mirex, endosulfan II, and dichlorodiphenyltrichloroethane and its metabolites) together within each site. We log-transformed the sum of the organic contaminants to minimize the effect of outliers and to linearize the relationship (if it exists) between sediment contaminants and hatching success. We analyzed the data for trends; kriging with a trend was used to interpolate data for the study area. Average total sediment contaminant load within 3 km of nest site was calculated.

*Distance to occupied osprey nest*.—We measured the Euclidean distance (m) of each unoccupied nest to the closest occupied nest by a spatial join. For occupied sites, we measured the Euclidean distance to the next-closest occupied nest using ET Geowizards 8.2 point distance tool (http://www.Ian-ko.com; 2002; ET Spatial Techniques, Pretoria, South Africa). Measurements were done in NAD83 Zone 18 UTM projection.

***Table 1.*** Variables examined in the osprey habitat and hatching success models, Delaware, USA, 2002.

| Variable | Delaware nest-occupancy model | Delaware hatching-success model[b] | Gulf of Maine (Banner and Schaller 2000) |
|---|---|---|---|
| Distance to occupied nest | +[a] | | + |
| Distance to water | + | | + |
| % agricultural land use | | + | |
| % marsh land cover | | + | |
| % shrub land cover | | + | |
| % urban land use | | + | |
| % water land cover | | + | |
| Presence of agricultural land use | + | | + |
| Presence of marsh land cover | + | | + |
| Presence of shrub land cover | + | | + |
| Presence of urban land use | +[a] | | + |
| Presence of water land cover | + | | + |
| Principle component 1 | | +[a] | |
| Principle component 2 | | + | |
| Total sediment organic contaminants | + | | |
| Water clarity | +[a] | | |
| Water depth | +[a] | | + |
| Wind speed | + | | |

[a] Variables retained in the final model.
[b] See Toschik et al. 2005.

*Distance to water*.—We measured the Euclidean distance (m) to water as the distance of a nest to the nearest part of the MDN GAP land use coverage classified as water, using a spatial join. Measurements were made in NAD83 Zone 18 UTM projection.

*Organic contaminant exposure*.—We chemically analyzed fresh sample eggs from 39 nests in the Delaware River and Bay; detailed analytical methods and results are reported elsewhere (Toschik et al. 2005). Total polychlorinated biphenyls (PCBs), *p,p′*-dichlorodiphenylethylene (DDE), chlordane and metabolites, heptachlor epoxide, and dioxin toxic equivalents (TEQs; a weighted average of toxic arylhydrocarbon receptor–active PCB congeners), were considered for the hatching-success model because they were found in highest concentrations relative to their known toxicity. We tested contaminant concentrations for homogeneity of variance and log-transformed the values to stabilize variances. Contaminant concentrations in eggs were strongly correlated; we conducted a principal components analysis (PCA) to clarify their effects and reduce the dimensionality of the list of explanatory variables. The TEQs were not individually correlated with egg hatching success, unlike the other 4 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 4 contaminants included in the analysis were weighted almost equally within the first component. Therefore, we retained the first component for use in the hatching-success model. The PCA including TEQs performed only slightly better, so we excluded TEQs from the final model. Because organochlorine contaminant concentrations in eggs could only be quantified at occupied nests, we could not incorporate this variable into the habitat-suitability model. The USGS, Patuxent Wildlife Research Center (12/05/

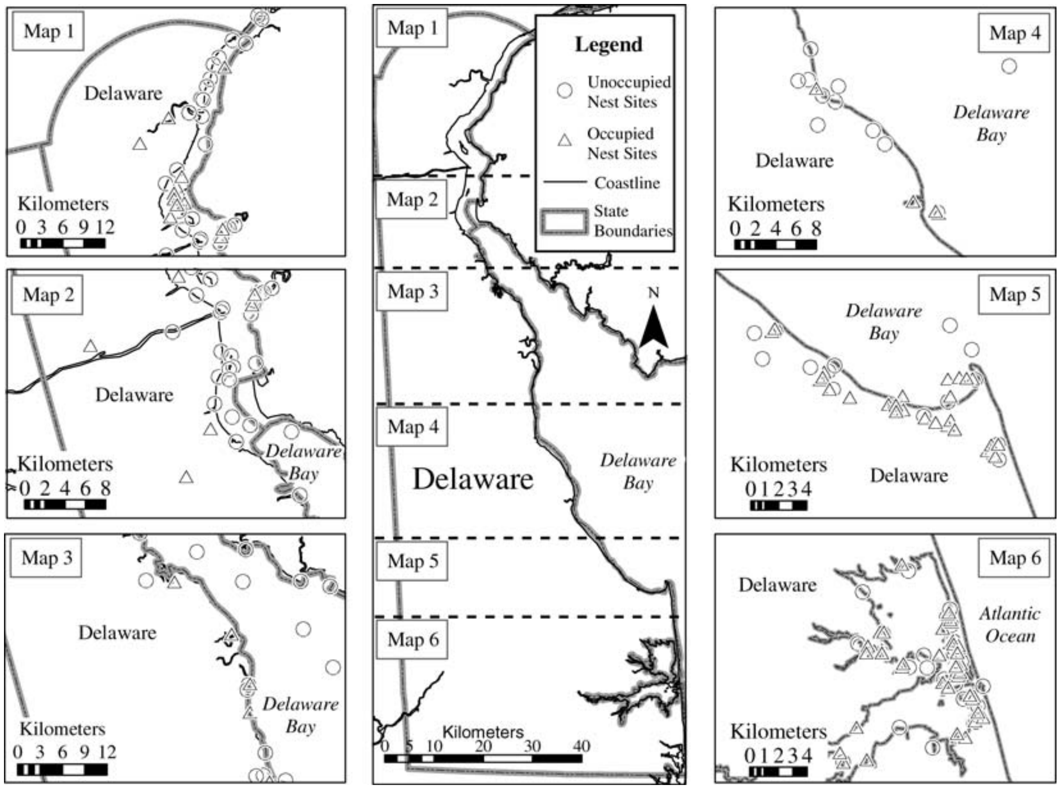


***Figure 2.*** Locations of occupied and unoccupied osprey nests overlaying combined land-use and land-cover classes in the Delaware River and Bay, 2002.

01) and the University of Maryland, College Park's Animal Care and Use Committees (R-0214A) approved the protocol for osprey egg sample collection and processing.

### *Methods for Evaluating Osprey Habitat Suitability: Logistic-Regression Model Development*

We developed a logistic-regression model for osprey nest occupancy using the variables described above (with the exception of organic contaminant exposure in eggs). We first examined potential explanatory variables ($n = 11$; Table 1) individually to determine whether they exhibited spatial variability. We excluded variables that did not exhibit spatial variability from the logistic-regression models. We selected the model with the all-possible-models approach (SAS Institute, Inc., Cary, NC), in which every combination of subsets of variables were tested. We selected candidate models of nest occupancy for further exploration based on model chi-square values. We further examined several models containing 3–5 variables. Akaike's Information Criterion (AIC) allowed us to determine whether the addition of model covariates improved the predictive capability of the model over an intercept-only model; this was evaluated for each individual model. We further evaluated covariate models in which the AIC difference ($\Delta$AIC) was $>5$. We examined the Pearson goodness-of-fit, $r^2$, percent concordant, false positive and false negative identifications, and the Hosmer–Lemeshow lack of fit to further narrow down the candidate best models. We selected the final model selection based both on the above review and the expected ease of access to similar data or expense of collecting similar data in other regions. We created a map of predicted osprey habitat use with the chosen model at points 0.005 degrees ($\approx$430 m) apart throughout the study area. Data gaps north of the Delaware State border limited predictive capability in this area, which limited our area of inference to Delaware State.

### *Methods for Comparing Model to an Existing Model*

The GOM model (Banner and Schaller 2000) used land use, proximity to water, water depth, and proximity to occupied nests to predict habitat suitability. Scrub habitat was identified as the preferred land use for ospreys in the GOM model (A. Banner, U.S. Fish and Wildlife Service, personal communication), so we ran the model with all land-use types (water, marsh, scrub, urban, and agriculture), as well as with a scrub habitat indicator only. The results were compared with the other models.

### *Methods for Evaluation of Osprey Hatching Success—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 hatching success. The model was initially developed using only contaminant concentrations as independent variables (Toschik et al. 2005); we examined habitat variables in conjunction with the contaminant variables to determine whether other habitat variables also affected hatching success. All variables ($n = 11$; Table 1) for the hatching-success model described above were included in the model, with several changes. The LULC data were summarized as a percentage of the buffer area, rather than being classified as present or absent. We included organochlorine contaminant concentrations in eggs in the model (total PCBs, $p,p'$-DDE, chlordane and metabolites, and heptachlor epoxide), as a linear combination based on the first principal component. The response variables were fledgling success (percentage of chicks

*Table 2.* Land-use and land-cover classes from Maryland/Delaware/New Jersey (MDN) Gap Analysis Program (GAP) map occurring within 0.2 km of occupied or unoccupied osprey nests or random points within the study area, Delaware Bay and River, USA, 2002.

| Map code | Map class | Occupied | Unoccupied | Random | Map code | Map class | Occupied | Unoccupied | Random |
|---|---|---|---|---|---|---|---|---|---|
| 400 | water | + | + | + | 431 | beachgrass shrublands | | | |
| 401 | tidal shallow/turbid | | | | 432 | dwarf beach shrublands | + | + | + |
| 402 | row crops | + | + | + | 433 | tidal cattail marsh | + | + | + |
| 403 | tidal herbaceous beach community | + | + | + | 434 | mixed pines for. | | | + |
| 404 | tidal high marsh | + | + | + | 435 | red pine for. | | | + |
| 405 | tidal marsh | + | + | + | 436 | red oak–white oak for. | + | + | + |
| 406 | tidal tallgrass marsh | + | + | + | 437 | nontidal sparsely vegetated beach alliances | + | + | + |
| 407 | lowland pine woodland | + | + | + | 438 | chestnut oak for. | | | + |
| 408 | mixed grass/low shrubs | + | + | + | 439 | beech–yellow poplar for. | | | |
| 409 | tidal maritime shrublands | + | + | + | 440 | high mountain shrub swamp | | | |
| 410 | coastal lowland pine for. | | | | 441 | mixed oak–sugar maple for. | + | + | + |
| 411 | coastal upland pine for. | + | + | + | 442 | rich northern hardwood for. | + | + | + |
| 412 | nontidal flooded herbaceous | + | + | + | 443 | freshwater tidal emergent marsh | | + | + |
| 413 | bare sand | + | + | + | 444 | redcedar woodland | | | + |
| 414 | cultivated trees | + | + | + | 445 | piedmont beech–oak for. | | + | + |
| 415 | loblolly–mixed oak for. | | + | + | 446 | tidal Atlantic white-cedar for. | | | |
| 416 | Virginia pine for. | | | | 447 | short-needled pine–mixed dry oak for. (pine barrens) | | | + |
| 417 | Virginia pine–mixed oak for. | | | + | 448 | pitch pine wet woodland | | | |
| 418 | coastal plain pine–mixed hardwood lowland for. | + | + | + | 449 | highbush blueberry–leatherleaf shrub swamp | | | |
| 419 | sweetgum swamp | | + | + | 450 | inland graminoid marsh | | + | + |
| 420 | mixed wet oak for. | | | | 451 | hemlock–mixed hardwood for. | | | + |
| 421 | coastal plain beech–oak for. | + | + | + | 452 | urban recreational grasses | | + | + |
| 422 | yellow poplar for. | | | | 453 | pasture/hay | + | + | + |
| 423 | sweetgum for. | + | | + | 454 | dune grassland | + | + | + |
| 424 | sycamore–mixed hardwood riverside for. | | + | + | 455 | nontidal tallgrass marsh | + | + | + |
| 425 | red maple–pumpkin ash swamp | | | + | 456 | nontidal mixed grass/low shrub | + | + | + |
| 426 | bald cypress tidal swamp | | + | + | 457 | nontidal maritime shrublands | + | + | + |
| 427 | urban | + | + | + | 458 | red maple–green ash swamp | | | + |
| 428 | lowland mixed oak for. | + | | + | 459 | nontidal mixed hardwood–conifer swamp | | + | + |
| 429 | bare/exposed/manmade features | + | + | + | 460 | nontidal cattail marsh | | + | |
| 430 | clearcut/transitional | + | + | + | 461 | nontidal Atlantic white-cedar for. | | | |

raised to fledging age per nest) and hatching success (percentage of eggs hatched per nest). We determined the optimum number of variables ($n = 1–3$) based on model chi-square values and then examined several candidate models. We employed the same model-selection procedure for the nest-occupancy model and the hatching-success model.

## RESULTS

### *Evaluation of Osprey Habitat Suitability—Individual Parameters*

*Water clarity*.—The mean secchi disk depth was 0.68 ± 0.022 m (mean ± SE) in buffers around occupied nests, 0.55 ± 0.019 m around unoccupied nest sites, and 0.57 ± 0.016 m for random points.

*Nest availability*.—Available nests were distributed unequally in the study area, with most available nests found around 38.6°N and 39.8°N latitude (Fig. 2). However, the distribution of occupied nests was strongly skewed to the south, with the most occupied nests found around 38.6°N latitude.

*Water depth*.—Of 131 buffers around occupied nests, 50 did not have depth data; the remaining 81 buffers had 298 or more depth points. Depth of water within 3 km of occupied 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 unoccupied 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 unoccupied 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 ± 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.

*Table 3.* Percentage of 0.2-km buffers around potential osprey nests and random points containing lumped land-use and land-cover (LULC) map classes, Delaware Bay and River, USA, 2002.

| Map class | Occupied | Unoccupied | 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 |

*LULC.*—Initial data showed that ospreys apparently preferred to nest over water, coastal marshes, or shrubs and avoided agricultural and urban areas (Table 2). Occupied, unoccupied, and random sites displayed different frequencies of occurrence of the lumped LULC classes ($P < 0.05$, chi-square test of independence; Table 3).

*Sediment contamination.*—Sediment organics were significantly correlated with all other variables in the nest-occupancy model (Pearson correlation, $P \leq 0.0001$). The data exhibited both latitudinal ($r^2 = 0.672$, $P < 0.0001$) and longitudinal ($r^2 = 0.128$, $P < 0.0007$) trends.

*Egg organochlorine contaminant exposure.*—The first principal component explained more than 90% of the variability in the principal components analysis of the contaminant concentrations in eggs, and so, was retained for the logistic-regression model of hatching success. The first component was almost equally representative of total PCBs, $p,p'$-DDE, chlordane and metabolites, and heptachlor epoxide. As these organochlorine concentrations in the eggs increased, probability of the egg hatching decreased. The equation representing this relationship was $\ln(p/(1-p)) = 0.3012 + 0.4782[\log_{10}(p,p'\text{-DDE}) + \log_{10}(\text{total chlordane metabolites}) + \log_{10}(\text{heptachlor epoxide}) + \log_{10}(\text{total PCBs})]$ (Toschik et al. 2005).

*Other variables.*—During model development, we considered other variables, including fish biomass, air pollution, and predation. However, no estimates that adequately addressed osprey forage fish or pressure on ospreys from predators were available, and air pollution data could not be specifically associated with exposure.

### Evaluation of Osprey Habitat Suitability—Logistic-Regression Model Performance

We identified several different models as candidates for the osprey habitat-suitability model (Table 4). The model selected as the overall best model to predict osprey nest occupancy used presence or absence of urban land use, water clarity, water depth, and distance to nearest occupied nest (for parameter estimates see Table 5). The classification table (Table 6) 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-occupancy model indicated that the probability cutoff for nest-occupancy predictions should be set at 0.40. At this probability, the false positive and negative identifications were minimized, and the sensitivity, specificity, and percentage of correct predictions were maximized. We mapped habitat quality and areas that the model predicts will have occupied nests ($\hat{P} \geq 0.40$) or unoccupied nests ($\hat{P} < 0.40$; Fig. 3).

Based on the most up-to-date information we used, with few exceptions, all habitats within the state of Pennsylvania and New Castle County, Delaware, USA, were classified as unsuitable for ospreys. In Pennsylvania, a few hectares near Neshaminy State Park and another small area near East Stroudsburg were identified as suitable habitat. In New Castle County, Delaware, a few hectares crossing over the border into Supawna Meadows National Wildlife Refuge in New Jersey, USA, and another small area near the mouth of the Appoquinamink River and Augustine Wildlife Area, were identified as suitable habitat. In Kent and

*Table 4.* Candidate models examined for predicting osprey nest occupancy, Delaware River and Bay, USA, 2002.

| No. variables | Variables | $\chi^2$ | $\Delta$AIC[a] | $r^2$ | % concordant | False + | False − | % correct | Lack of fit | $P$[b] |
|---|---|---|---|---|---|---|---|---|---|---|
| 2 | water clarity, distance to active nest | 80.7 | 89.8 | 0.035 | 78.8 | 38.2 | 14.6 | 73.6 | 0.47 | 0.46 |
| 2 | water depth, distance to active nest | 72.5 | 95.0 | 0.350 | 76.7 | 42.5 | 16.8 | 69.6 | 0.00 | 0.48 |
| 3 | water depth, water clarity, distance to active nest | 83.8 | 97.9 | 0.364 | 78.5 | 40.7 | 13.8 | 71.7 | 0.39 | 0.40 |
| 3 | water clarity, urban, distance to active nest | 83.6 | 99.5 | 0.366 | 79.2 | 39.9 | 14.1 | 72.3 | 0.10 | 0.42 |
| 4[c] | water depth, water clarity, urban, distance to active nest | 86.6 | 107 | 0.384 | 79.1 | 41.2 | 14.5 | 71.1 | 0.70 | 0.40 |
| 4 | water depth, water clarity, sediment organics, distance to active nest | 85.5 | 102 | 0.393 | 80.7 | 38.1 | 14.8 | 73.8 | 0.60 | 0.50 |
| 5 | water depth, water clarity, shrub, urban, distance to active nest | 87.7 | 106 | 0.387 | 79.7 | 39.1 | 17.9 | 72.0 | 0.25 | 0.48 |
| 5 | water depth, water clarity, agriculture urban, distance to active nest | 87.7 | 107 | 0.388 | 79.5 | 41.1 | 14.9 | 71.1 | 0.78 | 0.40 |
| GOM[d] | water depth, urban, marsh, agriculture, shrub, water, distance to active nest, distance to water | 73.9 | 94.6 | 0.358 | 77.3 | 42.5 | 16.8 | 69.6 | 0.13 | 0.46 |

[a] Difference between the Akaike's information criterion in the intercept-only model and the model with covariates.
[b] Probability is the cutoff above which a nest would be predicted to be occupied, and below which a nest would be predicted to be unoccupied.
[c] Selected as the best model of the candidate models.
[d] GOM = The Gulf of Maine model (Banner and Schaller 2000).

*Table 5.* Parameter estimates for the odds ratios of significant* variables in the Delaware, USA, osprey Habitat Suitability Model, 2002.

| Parameter | Maximum-likelihood estimate | SE | $\chi^2$ | *P* | Point estimate | LCL[a] | UCL[b] |
|---|---|---|---|---|---|---|---|
| Distance to occupied nest | −0.22 | 0.05 | 17.22 | <0.0001 | 0.80 | 0.73 | 0.89 |
| Presence of urban land use | −0.58 | 0.31 | 3.48 | 0.06 | 0.56 | 0.30 | 1.03 |
| Water clarity | 1.31 | 0.57 | 5.36 | 0.02 | 3.72 | 1.22 | 11.32 |
| Water depth | 0.13 | 0.07 | 3.05 | 0.08 | 1.14 | 0.98 | 1.31 |

[a] LCL = Lower confidence limit.
[b] UCL = Upper confidence limit.
* Significance = $P < 0.1$

Sussex counties in Delaware, large patches of suitable osprey habitat were identified. When compared with the actual occupied nest distribution, much of the suitable habitat in Sussex County was in use by ospreys, whereas we found few occupied nests in Kent County.

### Comparison to Other Models

The GOM model (Table 4), originally fit to real locations of osprey nests in Maine, performed similarly to the other models described in Table 4. The only shortcoming of the GOM model was its lower predictive capability compared with the Delaware Bay model derived herein. However, all variables used in the GOM were relatively inexpensive to collect, and the existing data are likely to be available for most locations. The comparability of the GOM model to the Delaware model was remarkable and was an indication that habitat requirements for ospreys are similar over a broad region.

### Evaluation of Osprey Hatching Success—Logistic-Regression Model Performance

We modeled hatching success using habitat variables, including contaminant concentrations in eggs. Although fledging success would have been a biologically relevant parameter to use, we could not model it because it did not exhibit a trend. Initial model-selection procedures indicated that the first 2 principal components, percentage of urban land use, water clarity, and water depth, could be useful in predicting hatching success (Table 7). However, the best model for osprey hatching success was the model using only the principal component, representing total PCBs, *p,p′*-DDE, chlordane and metabolites, and heptachlor epoxide (Toschik et al. 2005). Although the model fit and predictive capabilities were good, the hatching-success model did not perform quite as well as the habitat model (Tables 4, 7); however, it is still a useful model for obtaining a rough estimate of osprey hatching success at occupied nests.

## Discussion

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). Although confidence in the performance of these models is low, they are often the only resource for wildlife managers (Dettmers et al. 2002). However, in the present study, we employed logistic-regression models, which use presence/absence data, and performed quite well. These models can actually provide a suitable surrogate for abundance models for some species (Pearce and Ferrier 2001).

### Disparity of Nest-Site Use between Northern and Southern Delaware

Based on the nest-site use model, it is not surprising that few occupied osprey nests were found along the Delaware River north of the Chesapeake and Delaware Canal. Because the model included distance to nearest occupied nest as a parameter, nest-site philopatry and the semicolonial nature of ospreys may have been limiting the habitat quality and nest use in the northern region, solely, because most birds are breeding in the south. However, the unoccupied nest sites in the study area are largely within the dispersal range of ospreys from the southern area of Delaware and parts of the Chesapeake Bay. As such, the other parameters in the

*Table 6.* Classification table for osprey nest-occupancy model, Delaware Bay and River, USA, 2002.

| | Correct | | Incorrect | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| *P* level | Event | Nonevent | Event | Nonevent | % correct | Sensitivity | Specificity | False + | False − |
| 0.20 | 121 | 102 | 101 | 5 | 67.8 | 96.0 | 50.2 | 45.5 | 4.7 |
| 0.24 | 118 | 108 | 95 | 8 | 68.7 | 93.7 | 53.2 | 44.6 | 6.9 |
| 0.28 | 111 | 113 | 90 | 15 | 68.1 | 88.1 | 55.7 | 44.8 | 11.7 |
| 0.32 | 109 | 118 | 85 | 17 | 69.0 | 86.5 | 58.1 | 43.8 | 12.6 |
| 0.36 | 107 | 123 | 80 | 19 | 69.9 | 84.9 | 60.6 | 42.8 | 13.4 |
| 0.40[a] | 104 | 130 | 73 | 22 | 71.1 | 82.5 | 64.0 | 41.2 | 14.5 |
| 0.44 | 95 | 134 | 69 | 31 | 69.6 | 75.4 | 66.0 | 42.1 | 18.8 |
| 0.48 | 90 | 140 | 63 | 36 | 69.9 | 71.4 | 69.0 | 41.2 | 20.5 |
| 0.52 | 85 | 148 | 55 | 41 | 70.8 | 67.5 | 72.9 | 39.3 | 21.7 |
| 0.56 | 77 | 153 | 50 | 49 | 69.9 | 61.1 | 75.4 | 39.4 | 24.3 |
| 0.60 | 64 | 164 | 39 | 62 | 69.3 | 50.8 | 80.8 | 37.9 | 27.4 |
| 0.64 | 50 | 177 | 26 | 76 | 69.0 | 39.7 | 87.2 | 34.2 | 30.0 |

[a] Selected as the probability cutoff.

*Table 7.* Candidate models examined for predicting osprey egg loss, Delaware Bay and River, USA, 2002.

| No. variables | Variables | $\chi^2$ | $\Delta$AIC[a] | Deviance | $r^2$ | % concordant | False + | False − | % correct | Lack of fit | *P* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1[b] | principal component 1 | 6.07 | 3.66 | 0.056 | 0.104 | 64.5 | 41.7 | 20.0 | 77.0 | 0.20 | 0.40 |
| 2 | principal component 1, principal component 2 | 8.43 | 4.39 | 0.077 | 0.149 | 68.9 | 55.6 | 23.1 | 73.6 | 0.11 | 0.46 |
| 2 | water clarity, % urban land use | 9.28 | 2.64 | 0.055 | 0.131 | 62.3 | 50.0 | 16.9 | 76.5 | 0.07 | 0.34–0.36 |
| 2 | principal component 1, % urban land use | 7.93 | 2.46 | 0.055 | 0.119 | 64.8 | 45.5 | 21.1 | 75.9 | 0.23 | 0.36–0.38 |
| 3 | principal component 1, water clarity, % urban land use | 9.37 | 0.59 | 0.045 | 0.131 | 68.5 | 50.0 | 15.9 | 75.3 | 0.13 | 0.32 |
| 3 | principal component 2, water clarity, % urban land use | 12.4 | 4.22 | 0.082 | 0.184 | 72.5 | 56.3 | 13.2 | 70.6 | 0.56 | 0.24 |
| 3 | water clarity, marsh, % urban land use | 9.77 | 0.62 | 0.048 | 0.135 | 66.9 | 50.0 | 16.9 | 75.3 | 0.19 | 0.36 |
| 3 | water depth, water clarity, % urban land use | 9.37 | 0.48 | 0.044 | 0.130 | 62.8 | 52.6 | 18.2 | 74.1 | 0.11 | 0.36 |

[a] Difference between the Akaike's Information Criterion in the intercept-only model and the model with covariates; best model presented in Toschik et al. 2005.

[b] Selected as the best model of the candidate models.

osprey habitat model, water clarity and depth, and the presence of urban land use, indicate that the northern region is not prime osprey habitat, despite the availability of nest platforms.

## *Relative Importance of Contaminants and Other Habitat Factors*

Not surprisingly, the distance of a nest platform to another occupied nest was important in most candidate nest-occupancy models. This is likely a reflection on the semicolonial nature of ospreys in some areas, possibly related to high-quality habitat or high site fidelity. Information on osprey nest occupancy is relatively simple to collect, and it can be done rapidly from a helicopter in most places and via foot or boat in most others; it is both useful and readily available information for modeling osprey habitat anywhere. We also found water depth important in most of the candidate nest-occupancy models. Ospreys fish by sight and are limited by their leg length, to some extent, when foraging for prey items in water. Shallow water and clear water would both be expected to facilitate prey capture for ospreys. In most large water bodies, bathymetry data have been collected for shipping and scientific purposes and are easily obtained. Water clarity requires some time and effort to collect, although equipment and data analyses are simple. Land use was also an important factor in the candidate nest-occupancy models; these data are often available at the state or regional level.

Although ospreys have been observed nesting on a variety of natural and artificial nest structures, nearly 93% of the ospreys in the nearby Chesapeake Bay nested on artificial nesting structures, and some subpopulations nested exclusively on artificial structures (Watts et al. 2004). 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 yr; Poole 1989), and new platforms installed in these areas are immediately occupied (Watts et al. 2004). 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 and distribution of platforms and channel markers in Delaware could similarly be affecting that osprey population.

Other variables could also be used to model osprey habitat suitability but are somewhat more problematic. Air pollution data are available from the United States Environmental Protection Agency (USEPA), but the resolution of the data is very coarse, making estimation of exposure difficult. In theory, fish biomass could affect osprey nest occupancy, but calculating the biomass accurately and accounting for seasonal change are challenging, collecting the data is expensive, and the data are seldom readily available. Hypotheses regarding food availability may be best left to egg-exchange experiments when there is reasonable evidence of limitation at a specific site (Spitzer 1978), as it is unlikely that food would be a limiting resource for estuarine breeding ospreys. Although a relationship between nest locations and wind speed was expected, the limited data prevented elucidation of a potential relationship.

The relationship of osprey nest occupancy to water clarity could become far more relevant for conservation efforts if conditions in the bay area worsen. Plans to dredge Delaware Bay again (Army Corps of Engineers 1996) could produce water-clarity issues significant to ospreys and possibly other piscivorous birds on the bay. The 265,000-gallon Athos I oil spill in November of 2004, which occurred in the center of the study area, could have serious impacts on the breeding birds in the Delaware estuary. Nutrient issues in the Inland Bays could challenge the osprey population there if water clarity is further affected.

Although the logistic-regression model that included sediment contaminant data performed as well as, or better than, other nest-occupancy models, we did not include these data 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, yet expense of collecting such data in areas lacking sediment contaminant data would probably be prohibitive as part of a habitat evaluation. In addition, sediment contaminant concentrations were correlated with most other variables in the model, making it difficult to separate their effects on osprey

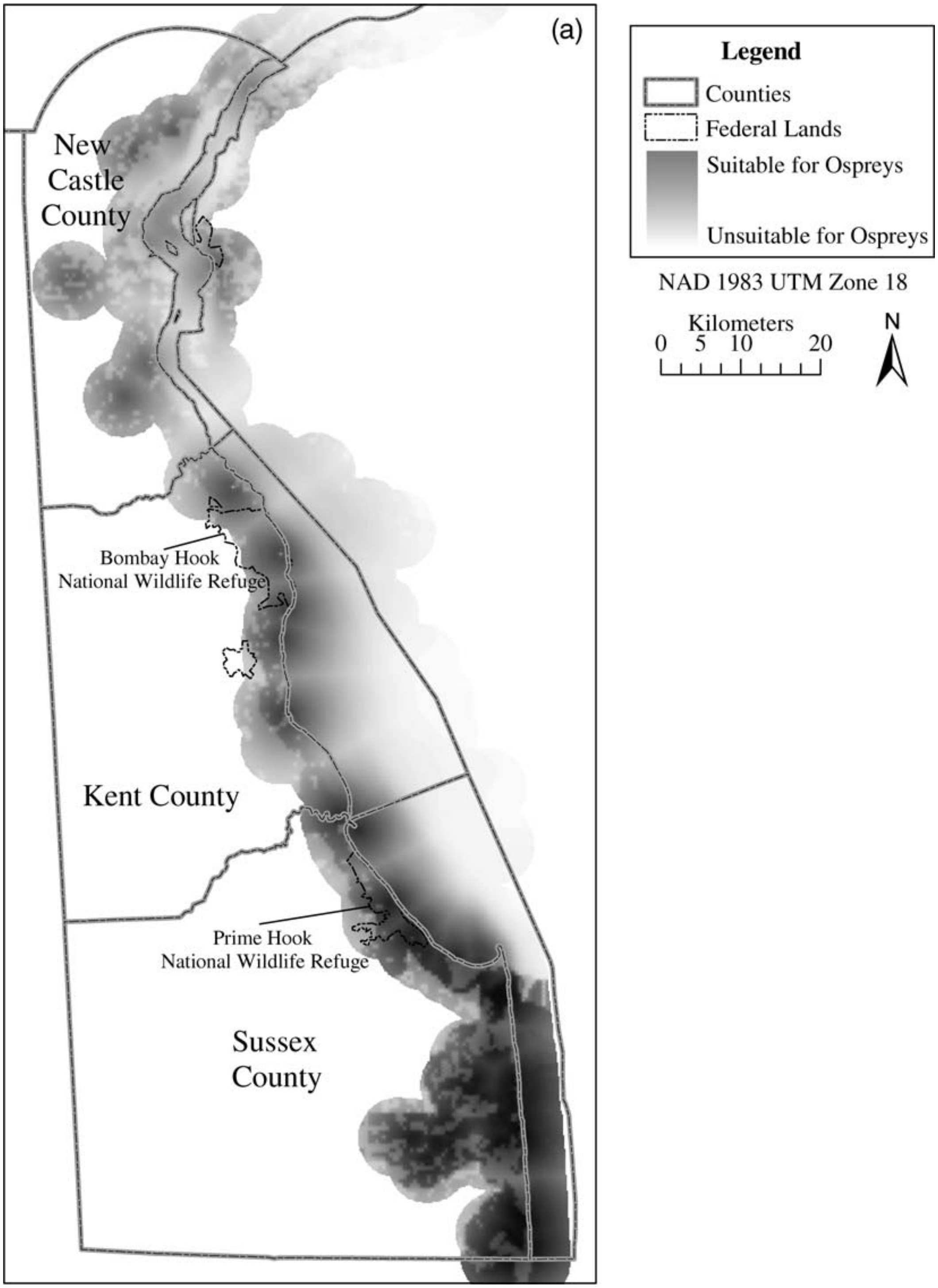


***Figure 3.*** Maps of predicted probabilities of nest occupancy. Map (a) shows the gradient of predicted probabilities of nest site use, whereas map (b) represents the cutoff at the 0.40 probability of nest-site use, as determined from the logistic-regression model. Notice very little osprey habitat is found in the northern region.

habitat use from the effects of other parameters in the model. Furthermore, replacing sediment contaminant concentrations with the urban land use parameter generated essentially the same nest-occupancy model and (if the data were not already available) would save a great deal of time and resources. Nonetheless, 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 hatching success than any other habitat parameters considered in our study (Toschik et al. 2005). It is remarkable that organochlorine contaminant exposure still shows effects on egg hatching. The contaminants may be an indicator of stress from anthropogenic 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 (Toschik et al. 2005).

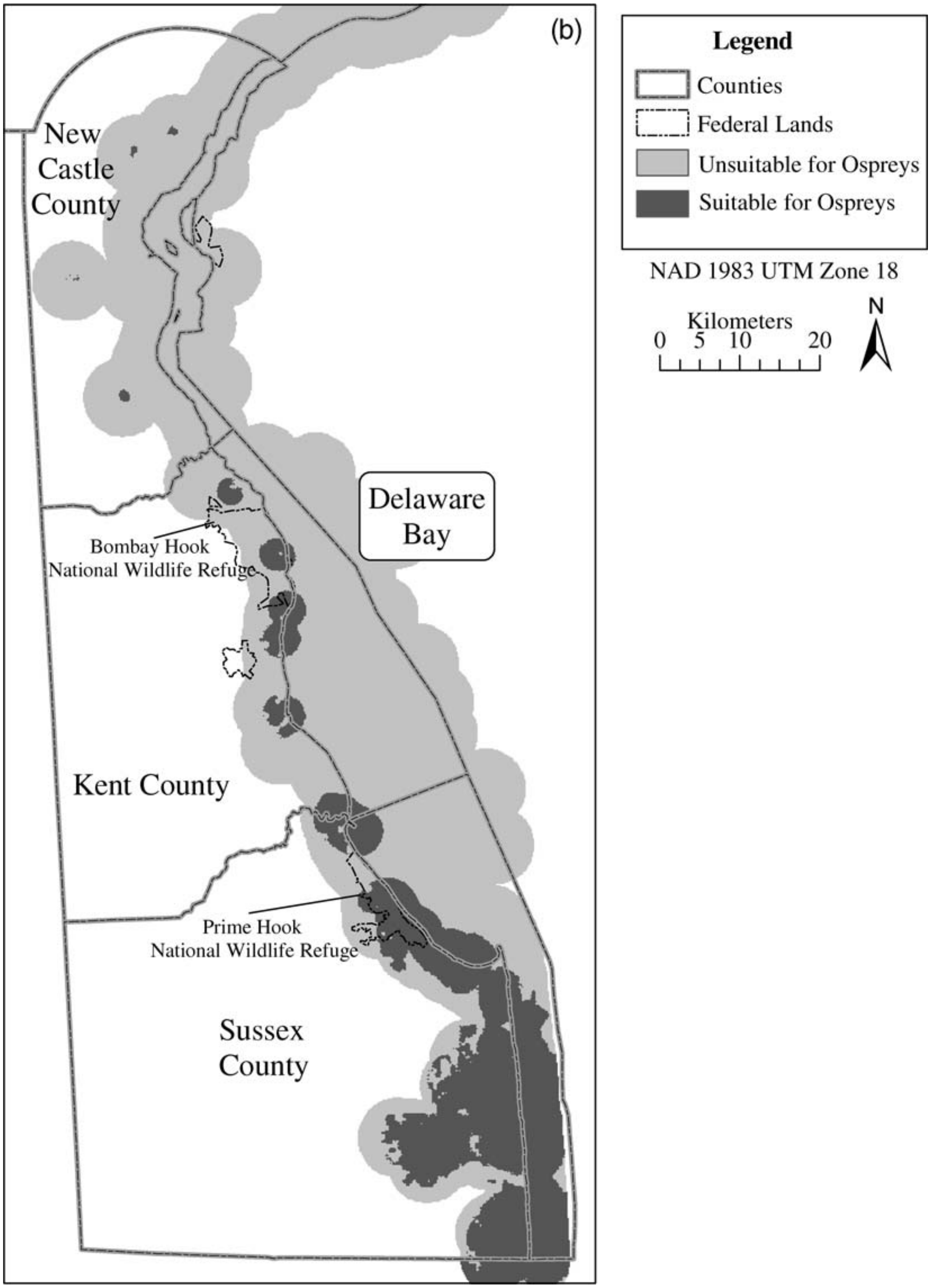


***Figure 3.*** continued.

## Management Implications

We presented several models for osprey habitat to allow habitat managers to select the best model for their region based on data availability. Where contaminant burdens are known, they are useful for modeling hatching success and the probability of nest-site use. Otherwise, when unavailable, nest-site use can be modeled using such parameters as urban land use. The current status of osprey populations in the United States justifies aerial nest surveys and water-clarity measurements with a secchi disk but not extensive or costly data collection. In selecting a model to use, managers should choose the best model for which empirical data can be obtained. In Delaware, future platform installations should be limited to areas near clear, shallow water, away from urban areas (>0.2 km) and away from sites where the 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 activities (e.g., measures that would improve water clarity, minimize dredging, and restore shallow coastal areas and marshland). Base data should be updated at regular intervals to focus osprey conservation efforts accurately. Of broader importance, HSI models developed solely from literature and expert opinion may provide the basis for modeling habitat suitability, but they must be fit to field data before use (see also Dettmers et al. 2002, Pearce and Ferrier 2001). We recommend that the models that we developed be tested at other locations to verify their applicability over a national or international scale.

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