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NORTH AMERICAN OSPREY POPULATIONS AND CONTAMINANTS: HISTORIC AND CONTEMPORARY PERSPECTIVES

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Osprey (*Pandion haliaetus*) populations were adversely affected by DDT and perhaps other contaminants in the United States and elsewhere. Reduced productivity, eggshell thinning, and high DDE concentrations in eggs were the signs associated with declining osprey populations in the 1950s, 1960s, and 1970s. The species was one of the first studied on a large scale to bring contaminant issues into focus. Although few quantitative population data were available prior to the 1960s, many osprey populations in North America were studied during the 1960s and 1970s with much learned about basic life history and biology. This article reviews the historical and current effects of contaminants on regional osprey populations. Breeding populations in many regions of North America showed post-DDT-era (1972) population increases of varying magnitudes, with many populations now appearing to stabilize at much higher numbers than initially reported in the 1970s and 1980s. However, the magnitude of regional population increases in the United States between 1981 (first Nationwide Survey, ~8,000 pairs), when some recovery had already occurred, 1994 (second survey, ~14,200), and 2001 (third survey, ~16,000–19,000), or any other years, is likely not a simple response to the release from earlier contaminant effects, but a response to multi-factorial effects. This indirect "contaminant effects" measurement comparing changes (i.e., recovery) in post-DDT-era population numbers over time is probably confounded by changing human attitudes toward birds of prey (shooting, destroying nests, etc.), changing habitats, changing fish populations, and perhaps competition from other species. The species' adaptation to newly created reservoirs and its increasing use of artificial nesting structures (power poles, nesting platforms, cell towers, channel markers, offshore duck blinds, etc.) are two important factors. The timing of the initial use of artificial nesting structures, which replaced declining numbers of suitable trees at many locations, varied regionally (much later in the western United States and Mexico). Because of the increasing use of artificial nesting structures, there may be more ospreys nesting in North America now than ever before. Now, with the impact of most legacy organic contaminants (DDT, other organochlorine [OC] pesticides, polychlorinated biphenyls [PCB], polychlorinated dibenzo-*p*-dioxins [PCDD], polychlorinated dibenzofurans (PCDF]) greatly reduced or eliminated, and some osprey populations showing evidence of stabilizing, the species was proposed as a Worldwide Sentinel Species for evaluating emerging contaminants. Several emerging contaminants are already being studied, such as polybrominated diphenyl ethers (PBDE) and perfluorinated acids and sulfonate compounds (PFC). The many advantages for continued contaminant investigations using the osprey include a good understanding of its biology and ecology, its known distribution and abundance, and its ability to habituate to humans and their activities, which permits nesting in some of the potentially most contaminated environments. It is a top predator in most ecosystems, and its nests are relatively easy to locate and study with little researcher impact on reproductive success.

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Ospreys (*Pandion haliaetus*) nest throughout much of North America (Figure 1) and are arguably the world's best known and most admired bird of prey (Poole, 1989), although peregrine falcons (*Falco peregrinus*) clearly have their following and were subjected to many of the same pollution problems (Cade & Burnham, 2003). The highly adaptable osprey, in recent years, reestablished itself in some of the most historically polluted urban landscapes in North America. This article discusses, with respect to North America, (1) the history of pesticide use, industrial pollutants, and other contaminants of concern, (2) the historical contaminant effects on osprey populations, (3) the initial and continued recovery of osprey populations following the DDT ban in 1972, (4) emerging contaminant issues in the 21st century, and (5) the future role of the osprey as a "worldwide sentinel species" for assessing and monitoring environmental contaminants in large rivers, lakes, reservoirs, and estuaries.

HISTORY OF PESTICIDE USE AND OTHER CONTAMINANTS OF CONCERN

The end of World War II marked the beginning of the modern era for synthetic organic pesticides. Prior to the mid-1940s, inorganic chemicals were used as pesticides, e.g., arsenic for the control of a variety of weeds and insects. DDT was the first notable organochlorine (OC)

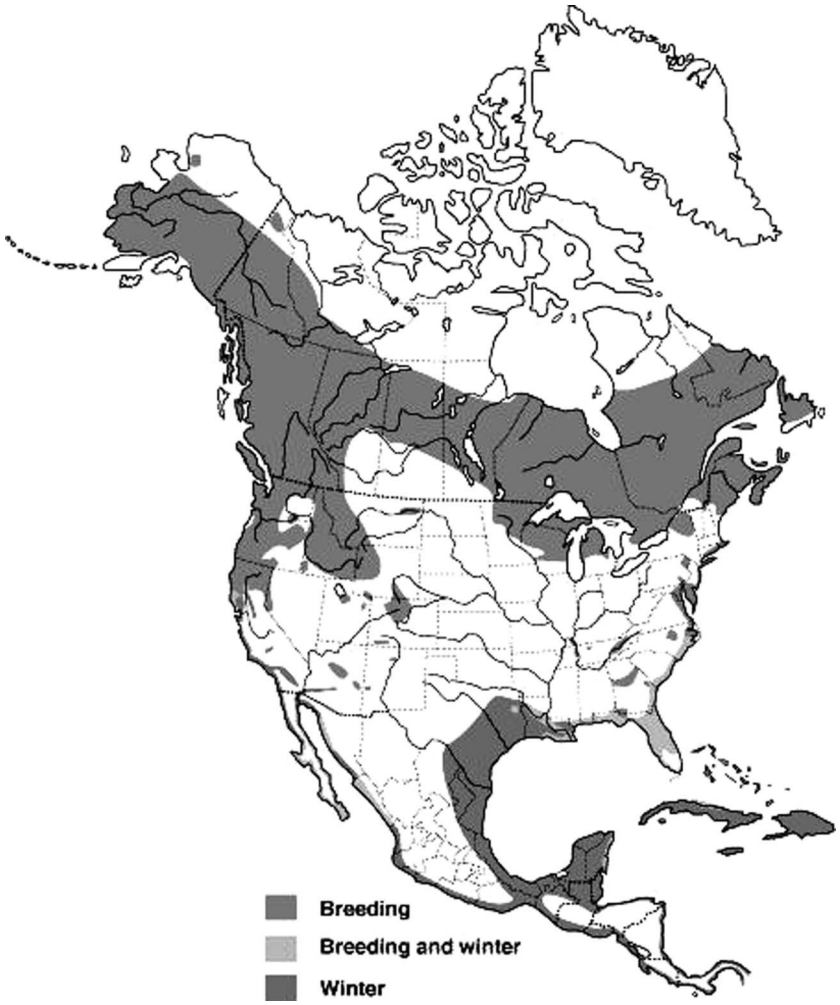

FIGURE 1. Distribution of ospreys breeding in North America (Poole et al., 2002).

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insecticide. It was first synthesized in 1874, but its properties as an insecticide were not discovered until 1939. Production of synthetic pesticides rapidly increased from 124 million pounds in 1947 to 638 million pounds in 1960 (Carson, 1962). DDT was widely used in the United States from 1945 onward, with two other OC insecticides (dieldrin and aldrin) widely used from 1950 and 1951 onward (Nisbet, 1988). Most OC pesticides were eventually banned in the United States beginning with DDT in 1972. The 1950s saw the development of two new major groups of insecticides, the alkyl or organic phosphates (e.g., malathion, parathion) and carbamates (e.g., carbaryl, carbofuran), which were generally less persistent, but in some cases, such as parathion and carbofuran, were more toxic. Other types of insecticides followed. Besides the insecticides, herbicides to control plants/weeds, fungicides to control plant parasites including rusts, mildews, and molds, and rodenticides to control small rodents, carnivores, and sometimes birds were developed post World War II (Rudd, 1964). According to sales and marketing data collected and evaluated by the U.S. Environmental Protection Agency, "almost 1 billion pounds" of conventional active pesticide ingredients was used in the United States in 1995 (Aspelin, 1997).

Besides pesticides, other contaminants of concern that may adversely influence osprey populations are industrial pollutants that find their way into the waterways and fish populations. Industrial pollutants include, but are not limited to, polychlorinated biphenyls (PCB), polychlorinated dioxins and furans (PCDD and PCDF), polybrominated diphenyl ether (PBDE) flame retardants, and perfluorooctane sulfonate (PFOS) compounds. The recent documentation of personal care products and pharmaceuticals in fish from U.S. waterways (Ramirez et al., 2009) also causes concern about their potential for accumulation and effects on fish-eating ospreys. Other naturally occurring elements of concern for ospreys and other water birds, when anthropogenically enhanced, include mercury, lead, cadmium and selenium.

HISTORICAL CONTAMINANT EFFECTS ON AVIAN POPULATIONS

When Carson (1962) and Rudd (1964) wrote their classic books about pesticides in the early 1960s, the osprey was not mentioned in either text. Later, Risebrough (1986) provided a useful review of the impacts of pesticides on bird populations, including direct mortality, lowered reproduction, modifications of behavior, and disruption of food webs. Two of the earliest studies revealing the potential hazards of DDT highlighted in Carson's book were (1) American robins (*Turdus migratorius*) dying with high DDT residue concentrations following its use to control Dutch elm disease in Wisconsin and Michigan during the 1950s, and (2) bald eagles (*Haliaeetus leucocephalus*) studied by Charles Broley along the west coast of Florida beginning in 1939 (Broley, 1952, 1958). In earlier years, Broley banded about 150 young eagles each year from about 125 nests. But between 1952 and 1957, about 80% of the nests failed to produce young, and in the last year only 43 nests were occupied and many unhatched eggs were reported (Carson, 1962). She also reported declining counts of birds of prey at migration count sites. Thus, the American robin and bald eagle were two species Carson (1962) used to focus attention on the pesticide issue. No detailed osprey studies were published during the 1950s, although some meaningful data was collected at the time and later published from Wisconsin; Gardiner's Island, NY; the Connecticut River; and Chesapeake Bay (Berger & Mueller, 1969; Puleston, 1975; Henny, 1977; Peterson, 1969; Henny & Stotts, 1975).

Little attention was specifically focused on the osprey in North America until Ames and Mersereau (1964) reported a rapidly declining population between 1960 and 1963 along the Connecticut River with extremely low productivity (0.29 young/nesting attempt). Their communications with investigators in adjacent states also indicated low osprey productivity. Several osprey eggs and fish collected in Connecticut contained DDT and DDE (the primary metabolite). These findings led to a segment of the 1965 Peregrine Falcon

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Conference at Madison, Wisconsin, being devoted to ospreys (Hickey, 1969). During the conference, exceptionally poor productivity or declining numbers were reported from Long Island, New York; Connecticut; New Jersey; Rhode Island; Maine; Massachusetts; and Wisconsin and Michigan. These "early warnings" resulted in the osprey in the United States being placed in the Redbook "Rare and Endangered Fish and Wildlife of the United States" and classified as "status undetermined" by the U.S. Fish and Wildlife Service (1966, 1968). In Canada, the species was classified "endangered" (Godfrey, 1970). These classifications probably were responsible for the osprey being studied in nearly every state and province where they occurred and resulted in a large attendance at osprey symposiums held at Williamsburg, VA, in 1972 and at Montreal, Canada, in 1981 (Ogden, 1977a; Bird, 1983).

In 1967, Ratcliffe (1967, 1970) proposed that major population declines of British raptors were correlated with the production of thin-shelled eggs that did not survive incubation. Then Hickey and Anderson (1968) related shell thinning specifically to DDE and mentioned a possible relationship between population status and general degree of thinning. Since then, a series of controlled laboratory studies showed that DDT or DDE fed to a variety of bird species resulted in reduced reproduction and the laying of thin-shelled eggs (Heath et al., 1969; Wiemeyer & Porter, 1970). In 1972, Anderson and Hickey (1972) reported that osprey eggs collected in Connecticut, New Jersey, and Maryland in 1957 had shells 15–18% thinner than pre-1947 shells.

Most localized osprey studies included an evaluation of reproductive success and changes in population numbers over time (although few series were available with long-term data), an evaluation of some eggs and fish for contaminant residues, and an evaluation of eggshell thickness. Since reproduction was the apparent weak link in the life cycle, the number of young fledged per nesting pair was recorded and considered of primary importance. Structural population modeling, based upon survival rate estimates from banding data and life history characteristics (Henny & Wight, 1969; Henny et al., 1970), was used to estimate a recruitment standard (0.95–1.30 young/nesting pair) needed to maintain a stable population. At that time, most populations were producing at what was believed to be extremely low rates, with the normal rate (or standard) unknown. The observed production rates were compared to the standard, which was later lowered to 0.80 young/nesting pair, based upon the observed population response compared to the projected population response based upon the model (Spitzer, 1980; Spitzer et al., 1983).

THE EARLY OSPREY STUDIES: 1950s, 1960s, 1970s

Available reproductive success data and population numbers for various North American osprey populations from 1950 to 1975 were summarized on a regional basis at the First World Conference on Birds of Prey at Vienna, Austria, in 1975 (Henny, 1977). The North Atlantic Coast population, where both reproductive data and population numbers were available, showed a continuous population decline through 1975, with the highest annual rates of decline between 1960 and 1970 (Table 1). Similarly, the associated production rates were the lowest between the late 1950s and the early 1970s. Farther south along the Atlantic Coast in Delaware, Chesapeake Bay, and North Carolina, substantial populations remained and observed production rates during the 1960s and early 1970s were variable (Figure 2). Eastern Bay and the Potomac River of Chesapeake Bay were particularly low. Several long-term studies of ospreys in the Great Lakes Region by Berger and Mueller (1969) and Postupalsky (1977) showed productivity patterns in Wisconsin and Michigan (Figure 2) that paralleled those observed along the North Atlantic Coast. Productivity rates began decreasing in the 1950s and continued to decrease into the early 1960s. The widely scattered osprey populations in the western United States were not studied until the late 1960s; thus, it was not known whether productivity there was

TABLE 1. Breeding Population Changes and Productivity of Ospreys Along the North Atlantic Coast of the United States and Canada, 1945–1975

	Number occupied nests				
Location	Pre-1945	1960	1965	1970	1975
Gardiner's Island, NY	300	100	70	38	31
Connecticut River, CT	200	71	13	4	1
Rhode Island	130	60+	23	7	8
Southern New Jersey	253	NA	NA	45	31
Brigantine N.W. Refuge, NJ	NA	NA	NA	6	4
Westport River, MA	NA	NA	15	16	15
Subtotals[a]	630	231+	106	49	40
Observed annual rate change (%)	−6.5	−14.4	−14.3	−4.0	

	Number young fledged/occupied nest					
Location	1950–1952	1953–1957	1958–1962	1963–1967	1968–1972	1973–1975
Gardiner's Island, NY	1.19	0.83	0.75	0.16	0.53	0.68
Connecticut River, CT	NA	0.37	0.23	0.33	0.25	0.00
Rhode Island	NA	NA	0.27	0.40	0.61	1.00
Subtotals[a]	1.19	0.65	0.47	0.23	0.52	0.73
Southern New Jersey	NA	NA	NA	NA	0.28	0.54
Brigantine N.W. Refuge, NJ	NA	NA	NA	NA	0.42	0.73
Westport River, MA	NA	NA	NA	0.60	0.84	1.24
Maine	NA	NA	NA	0.38	0.98	1.19
Nova Scotia, Canada	NA	NA	NA	NA	NA	1.22
Labrador, Canada[b]	NA	NA	NA	NA	0.75	NA

Note. Adapted from Henny (1977). NA, not available.

[a]Pooled data for Gardiner's Island, Connecticut River, and Rhode Island (see Henny, 1977, for more information, including specific citations).

[b]Wetmore and Gillespie (1977).

as low in the 1950s and early1960s as it was along the North Atlantic Coast and the Great Lakes Region. Studies of production rates in the West in the late 1960s and early 1970s were limited to a few locations and generally reported values in the near-normal or normal range, except at Yellowstone National Park. Similarly, an early study in Mexico in 1971 reported a productivity rate of 1.1 young per occupied nest (Anderson 1972) which was also within the normal productivity range. In summary, reproductive rates varied among locations in the 1950s, 1960s, and early 1970s, with some populations showing extremely low production rates.

WHAT ROLE DID DDT HAVE IN OSPREY POPULATION DECLINES?

What role did DDT and perhaps other contaminants play in the declines of osprey populations? The answer rests in the timing of population declines relative to pesticide/contaminant use, residues found in eggs and eggshell thickness, and causes of adult mortality. The use of DDT in the United States began in the mid-1940s (average tons/year active ingredient used: 1946–1950, 18,840; 1951–1955, 28,380; 1956–1960, 32,866; 1961–1965, 26,910; 1966–1970, 15,945; 1971–1972, 9,091 [Nesbit, 1988]) and continued until the nationwide ban in 1972. However, domestic use dropped about 50% between 1956–1960 and 1966–1970, including reduction of its use for large-scale forest insect control operations, mosquito control programs, and many agricultural uses (Mrak, 1969). DDT was still in common use particularly along the North Atlantic Coast for mosquito control; e.g., Suffolk County Mosquito Control commission, Long Island, New York, routinely sprayed DDT every spring and summer from the late 1940s to 1966,

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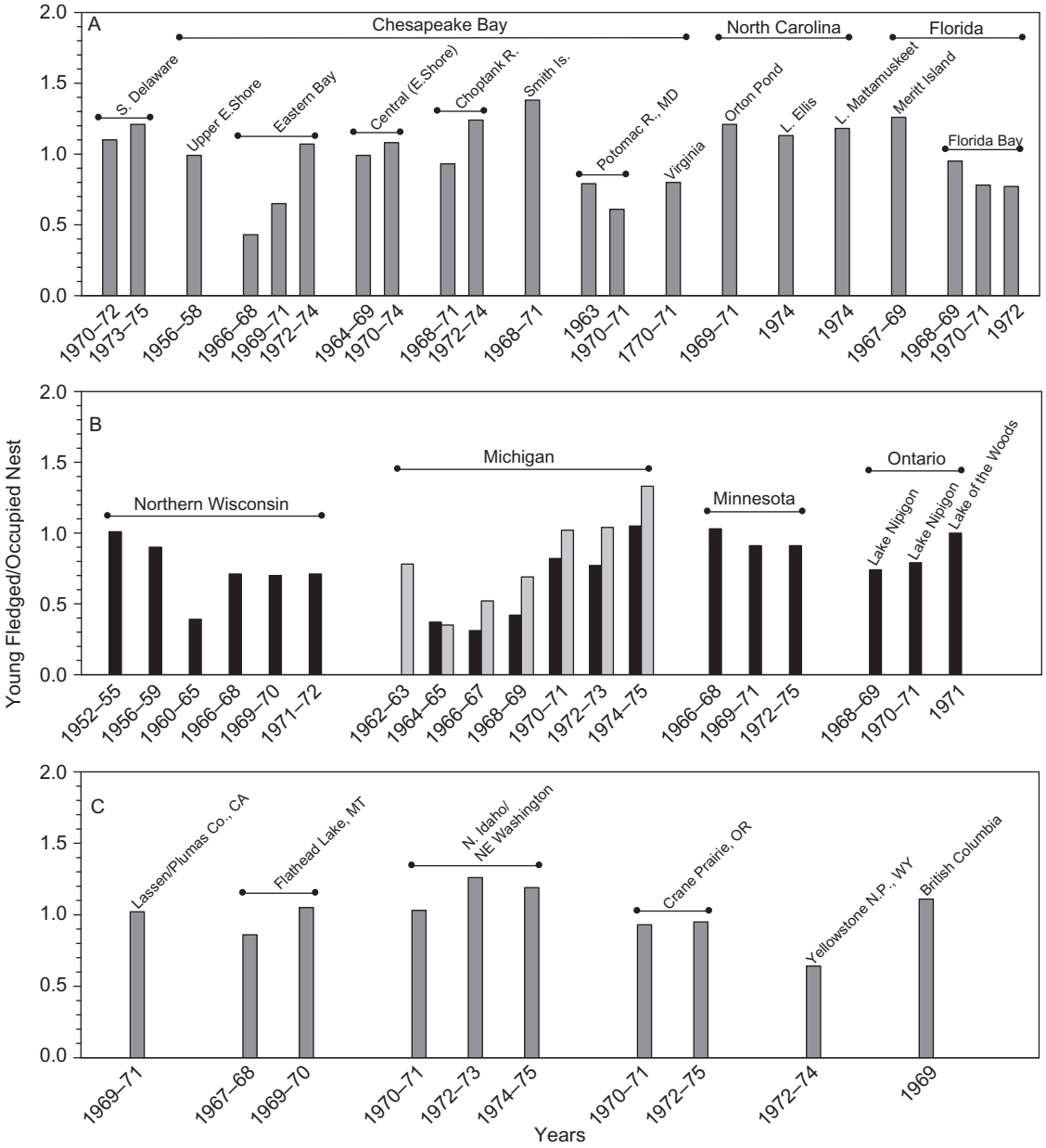

FIGURE 2. Productivity (young/occupied nest) of ospreys in the 1950s, 1960s, and 1970s along the south Atlantic Coast (A), the Great Lakes (B), and western North America (C). For Michigan in (B), the gray bars denote the lower peninsula and the black bars the upper peninsula (see Henny, 1977, and Ogden, 1977b, for more information including citations).

when a lawsuit ended the practice (Puleston, 1975). Aldrin (which readily converts to dieldrin) and dieldrin use began later (average tons/year active ingredient combined) and continued longer: 1950, 662; 1951–1955, 1,739; 1956–1960, 3,876; 1961–1965, 6,568; 1966–1970, 6,963; 1971–1975, 4,630; 1976, 409 (Nesbit 1988).

Wiemeyer et al. (1975) noted that Connecticut osprey eggs in 1967–1969 had shells 15 to 18% thinner than pre-1947 shells, and Maryland eggs in 1968–1969 showed only 10–12% thinning. Production was below normal in Connecticut in the late 1960s, while production in portions of Chesapeake Bay was normal or near-normal. Wiemeyer et al. (1975)

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found lower DDE residues in Maryland eggs than Connecticut eggs for 1968–1969. From this and the results when eggs were exchanged between Maryland and Connecticut, it was concluded that the most probable cause of poor reproduction of Connecticut ospreys was DDE contamination of the birds and their eggs. Spitzer et al. (1978) evaluated unhatched eggs collected between 1969 and 1976 from Connecticut and Long Island, New York. Egg residues were summarized by the number of young produced at each nest (0, 1, and 2 young). Geometric mean DDE concentrations (dry weight) were 113 ppm (22.6 ppm wet weight, assuming 80% moisture content), 59.6 ppm (11.9), and 29.1 ppm (5.82), respectively. Spitzer (1980) further reported that DDE in osprey eggs declined fivefold (estimated from a figure and again converted from dry to wet weight) between 1969 (24 ppm) and 1976 (4 ppm) and approximately threefold since 1973 (13 ppm), while polychlorinated biphenyls (PCB) showed no significant changes between 1969 and 1976 as productivity increased. Note that all residue concentrations in the remainder of this article are reported in ppm (wet weight). Later, Wiemeyer et al. (1988) reported that 15% and 20% eggshell thinning of osprey eggs was associated with 4.2 and 8.7 ppm DDE. Lincer (1975) reported that no North American raptor population that exhibited 18% or more eggshell thinning was able to maintain a stable population. Much residue data from osprey eggs is available for evaluation, but before further evaluating production rates and egg residues, contaminant-related mortality of adults is reviewed.

CONTAMINANTS AND DIRECT MORTALITY OF OSPREY ADULTS

Wiemeyer et al. (1975) suspected that dieldrin may have increased the adult mortality rate of ospreys in Connecticut, and reported a lethal concentration in the brain of an adult male that died on June 29, 1967. A bald eagle, also from Connecticut in 1967, was suspected of dying from DDT/DDD poisoning (Reichel et al., 1969). Another adult osprey was believed poisoned by dieldrin in South Carolina on April 20, 1970 (Wiemeyer et al., 1980). None of 29 dead ospreys evaluated died of DDE poisoning (Wiemeyer et al., 1975, 1980). The Connecticut population appeared to decline more rapidly than reproductive failure alone would predict. However, the precipitous population decline from 71 nesting pairs in 1960 to 31 pairs in 1961 may be at least partially explained, as suggested by Henny and Ogden (1970), by catastrophic mortality associated with the worst hurricane (Donna) in decades during fall migration (September 1960). Peakall (1996) reviewed the causes of death of bald eagles (eat fish, but also other prey including birds) found dead in the United States by a network of federal, state, and private investigators from 1966 to 1983. The percent of deaths attributed to dieldrin decreased after 1966–1970 (peak dieldrin use), i.e., 1966–1970, 13%; 1971–1974, 6.5%; 1975–1977, 3.0%; and 1978–1983, 1.7%. While Nisbet (1989) considered that both reproductive impairment produced by DDE and excess bald eagle adult mortality produced by dieldrin appear to have contributed to regional population declines, Peakall (1996) concluded that the evidence was circumstantial at best. The two dieldrin-related osprey deaths both occurred during the 1966–1970 peak use period. And Peakall (1996) concluded that reproductive processes of birds were not particularly sensitive to dieldrin.

Both dieldrin and aldrin, although widely used in agriculture, were primarily used in the corn belt of the midwestern United States and the cotton belt of the southern United States, which is outside the breeding range for most ospreys. Migrant passerines and other avian species, accumulating dieldrin and aldrin while travelling through these agriculture zones, would not influence contaminant loading in fish-eating ospreys nesting farther north, but, as pointed out by Nisbet (1988), might accumulate in bird-eating peregrine falcons. Thus, the potential importance of dieldrin/aldrin-related direct mortality for ospreys seems lower than for the peregrine falcon and perhaps the bald eagle, which often preys on birds. Other

legacy contaminants certainly may have played a role in local osprey population declines, e.g., dioxins and furans (Woodford et al., 1998), but DDT and it metabolites, with its resulting effects on eggshell thickness and productivity, appear to be the dominant factor.

DDE, REPRODUCTIVE EFFECTS, AND RECOVERY OF OSPREY POPULATIONS

DDE is primarily responsible for eggshell thinning, with egg residue data summarized by region, location, and year (Figure 2). To aid in interpreting the information, the percent incidence of DDE concentrations ≥4.2 ppm and ≥8 ppm was evaluated when available. The two effect categories (moderate and high) were based upon Wiemeyer et al. (1988) except the high category was lowered slightly from 8.7 to 8 ppm, which more closely approximates 18% eggshell thinning. Reproductive rate information (based upon nests with one egg randomly collected and chemically analyzed) further supported these effect classifications (see reproductive information and eggshell thickness in Henny et al., 2004). Nests with an egg collected that contained ≥4.2 ppm DDE produced 22% fewer young compared to those with an egg that contained <4.2 ppm. An egg containing ≥8 ppm DDE produced 38% fewer young, but the specific value in the high category would depend upon the distribution of egg concentrations above 8 ppm, with higher percentages of failure possible with increasing distance above 8 ppm. Some earlier egg residue data presented on a lipid basis were not used in this report; lipid content varies with embryo development, and concentrations could not be reliably converted to wet weight. Many of the earlier series of data were from unhatched eggs found in the nests. Wiemeyer et al. (1988) noted that DDE concentrations in osprey eggs that failed to hatch appeared unreliable in predicting eggshell thickness in the higher range of concentrations, because eggs with the thinnest shells appeared to have been lost, presumably to breakage. Thus, eggs with higher concentrations of DDE that "failed to hatch due to breakage" would not be represented in the failed eggs collected for residue analyses in earlier years. The broken eggs not included result in a potential bias low for geometric mean DDE concentrations based upon failed eggs collected in earlier years. However, at several locations where both random fresh and failed eggs were collected in more recent years, but with generally lower DDE concentrations, similar geometric mean concentrations were reported for the two types of egg collections. Thus, both types of egg collections appeared to represent the population in more recent years when serious eggshell thinning no longer occurred.

Eastern Populations

DDE residue data from ospreys in the Northeastern United States included some extremely high concentrations (e.g., 21, 22, 24, 26, 40 ppm) reported in the 1960s and 1970s (Ames, 1966; Wiemeyer et al., 1975, 1978, 1988) (Figure 3). In addition, an extremely high geometric mean DDE concentration was reported in eggs from nests that failed in Connecticut and Long Island, New York (22.6 ppm) (Spitzer et al., 1978). DDE in eggs from Maryland and Virginia seldom exceeded 10 ppm during the same time period (Ames, 1966; Wiemeyer et al., 1975, 1978, 1988). Only a limited number of eggs were collected in North Carolina and Florida in the 1960s and 1970s, with no concentrations above 5.4 ppm (Ogden, 1977b; Wiemeyer et al., 1988). Seven random fresh eggs from the Great Lakes Region (Lake of the Woods, Ontario) in 1971 (adjusted from dry to wet weight) contained a geometric mean of 4.1 ppm (4 eggs [57%] ≥4.2 ppm) with an extreme of 8.4 ppm (Grier et al., 1977).

By the 1980s and 1990s, no eggs collected along the North Atlantic Coast contained DDE at >5.2 ppm, and few contained concentrations ≥4.2 ppm (Steidel et al., 1991; Clark et al., 2001) (Figure 2). The limited number of eggs collected from the southeastern United States in the 1980s contained no DDE >3.0 ppm (Audet et al., 1992). From the Great Lakes Region, eggs collected from Wisconsin and Michigan in the 1980s and

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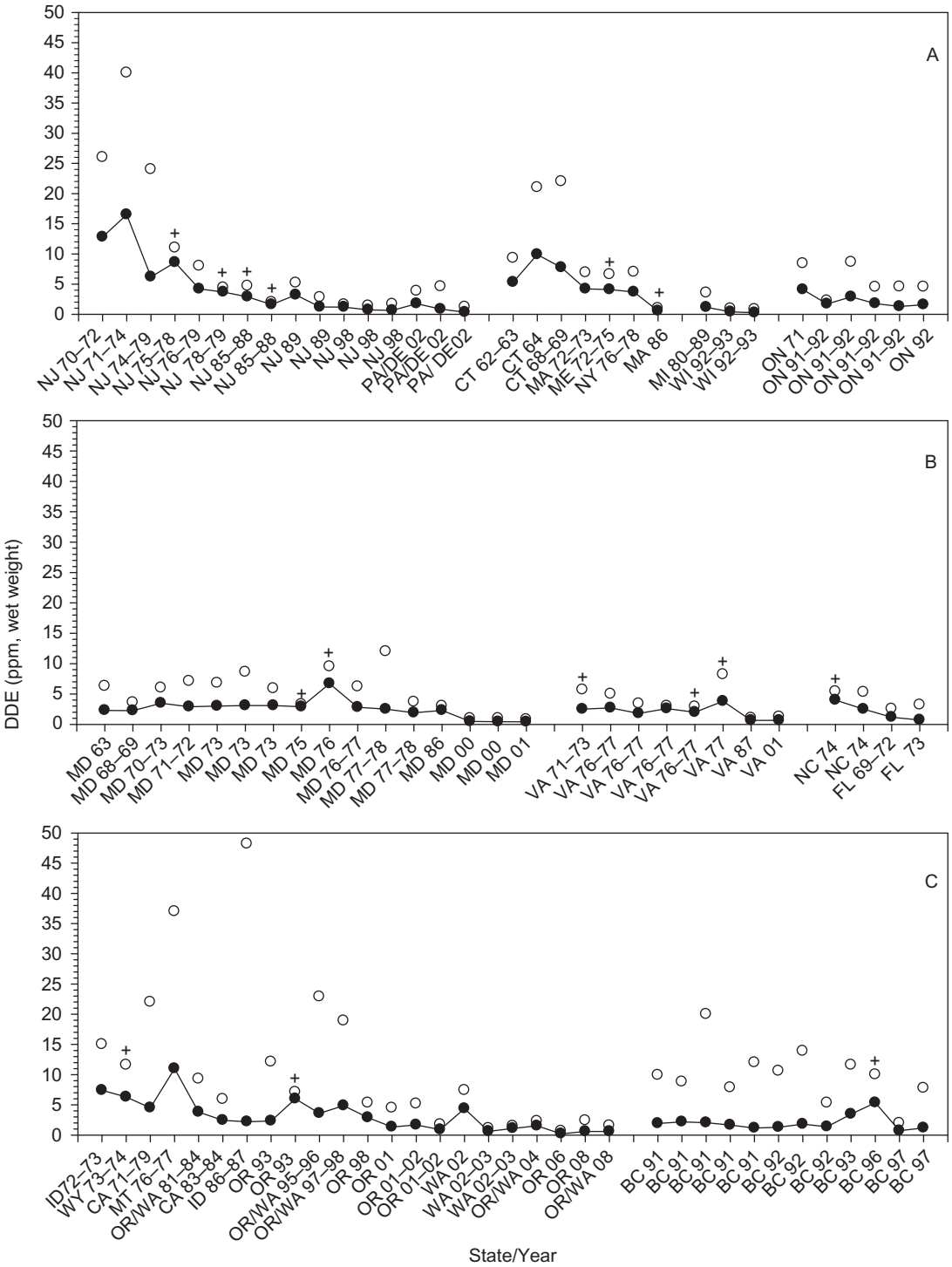

FIGURE 3. Geometric mean concentrations (ppm, ww) and high value of DDE in osprey eggs from the northeastern United States and Canada (A), southeastern United States (B), and the western United States and Canada (C). +, Years and states with <5 eggs collected.

early 1990s contained no DDE concentrations >3.55 ppm (Woodford et al., 1998; Ewins et al., 1999), while in Ontario (dependent on location) 0–20% of the eggs contained ≥4.2 ppm with a high of 8.64 ppm (Martin et al., 2003).

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Improvement of osprey productivity in seriously affected areas paralleled the decreased use of DDT (recall 50% reduction between 1956–1960 and 1966–1970) and other persistent chemicals. Populations on Long Island, New York; Connecticut; and Rhode Island combined (the most complete data set) from many investigators showed the lowest productivity in the mid-1960s (0.23 young/occupied nest) with gradual increases through the mid-1970s (0.73), although still below the recruitment standard (normal rate), with similar findings in southern New Jersey (Table 1). Improvements to a normal production rate were reported in Massachusetts by Fernandez and Fernandez (in Henny, 1977) and in Maine by Kury (1966) and Johnston (1974) (Table 1). Similarly, production rates in the Eastern Bay of Chesapeake Bay collected by Reese (1975) showed a steady increase from 1966–1968 to 1972–1974, with the latter time period again in the normal range. In coastal Delaware, productivity data collected by Todd (Henny et al., 1977) from 1970–1975 were consistently in the normal range (1.15). The long-term data set for Michigan collected by Postupalsky (1977) showed that production rates bottomed in the mid-1960s, but steadily increased to the normal range by 1970–1971, and continued to increase by 1974–1975. However, by the mid-1970s, there was little evidence of a population recovery taking place at any of the most severely affected locations. Ospreys do not reach sexual maturity until at least 3 years of age (Poole et al., 2002), which delays the timing of a population recovery after recruitment improves to normal/above normal.

Several of the populations mentioned in Table 1 continued to be monitored, including Gardiner's Island, New York, where 31 pairs nested in 1975. By 1986, the number increased to 48 pairs, but declined to 41 pairs in 2000 and 36 pairs in 2001 (Poole et al., 2002). The significant decline in number of breeding pairs was apparently related to lack of accessible food, perhaps made worse by expanding populations of double-crested cormorants (*Phalacrocorax auritus*), a species that was also impacted by DDE (Anderson & Hickey, 1972). The Rhode Island osprey population increased from 8 pairs in 1975 to 25 pairs in 1986 to 58 pairs in 2000 (Poole et al., 2002). The Kawartha Lakes region of Ontario, Canada, was monitored from 1978 to 2000 (de Solla et al., 2003). The number of occupied nests increased from 18 in 1978 to 89 in 1992 followed by 78 in 1996 and 66 in 2000, suggesting a recent decline or population stabilization. The mean production rate between 1986 and 2001 was 1.17 young per occupied nest. Updated information on a regional basis is not available, but population responses at other locations are mentioned later in this article.

Western Populations

Eggs collected from the western United States in the 1970s showed relatively high DDE residues in Idaho (55% $\geq$8 ppm) (Johnson et al., 1975), Wyoming (50% $\geq$8 ppm) (Swenson, 1979), Montana (67% $\geq$8 ppm) (Wiemeyer et al., 1988), and northern California (21% $\geq$8 ppm) (Littrell, 1985), with some especially high values, e.g., 37 ppm in Montana. The nesting osprey populations along the Willamette and lower Columbia Rivers in Oregon and Washington were nearly decimated by 1976 (Henny et al., 1978a) with no eggs collected. Later studies along the Willamette and Columbia Rivers in Oregon and Washington evaluated possible continuing effects of persistent legacy contaminants and evaluated emerging contaminants (later in this report). The osprey population along the lower Columbia River was only surveyed on the Oregon side in 1976 (Henny et al., 1978a), but the total population was probably <10 nesting pairs. Gabrielson and Jewett (1940) reported the species formerly common along the Columbia and Willamette Rivers.

Although much more data were collected in the eastern United States during the 1950s–1970s, the recovery of several population segments of ospreys was monitored more closely in the Pacific Northwest in the 1980s, 1990s, and 2000s. Eggs regularly contained DDE concentrations $\geq$8.0 ppm, including 29% of

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eggs collected in Oregon and Washington in 1981–1984 (Henny & Anthony, 1989), 33% in 1995–1996 (Elliott et al., 2000), and 24% of a large series (29 eggs) collected along the lower Columbia River in 1997–1998 (Henny et al., 2004). Nine percent of osprey eggs from Idaho in 1986–1987 contained ≥8.0 ppm (Henny & Anthony, 1989; Henny, personal communication). During the 1980s and 1990s, 20–66% of the Pacific Northwest eggs contained ≥4.2 ppm DDE. By the 2000s, no eggs from the Pacific Northwest contained ≥8.0 ppm, but in 2001/2002 some eggs from the upper Willamette River (9%), Santiam River (20%), and Yakima River (80%) continued to contain ≥4.2 ppm DDE (Henny et al., 2008a, 2009a, 2009b). By 2004 and 2006, no eggs from the lower Columbia or upper Willamette Rivers contained DDE residues at >2.29 ppm (Henny et al., 2008a, 2009b). Production rates (young/occupied nest) along the Willamette River at nests without an egg collected for residue analyses were: 1993 (1.58), 1998 (1.74), 1999 (1.59), 2000 (1.60), 2001 (1.67), 2008 (0.90), and 2009 (1.09) (Figure 4).

The osprey was among the first species of fish-eating and raptorial birds to show indications of a regional pattern of eggshell thinning (Hickey & Anderson, 1968; Anderson & Hickey, 1972; Spitzer et al., 1977). The large series of 238 eggs collected in Oregon, Washington, and Idaho during the last 40 years shows the classic semi-log relationship between DDE and eggshell thickness (Figure 5), and a decrease in DDE concentrations at all locations overtime following the 1972 ban on DDT (Figure 6). DDE in osprey eggs from the Willamette River in 1981–1982, 1993, and 2006 pertained only to the Upper River, where DDE residues were generally lower than farther downstream—hence their somewhat lower concentrations when compared to the other years when the complete river was represented (see Figure 6). Osprey numbers (occupied nests) along the Willamette River (including a portion of the Santiam River)

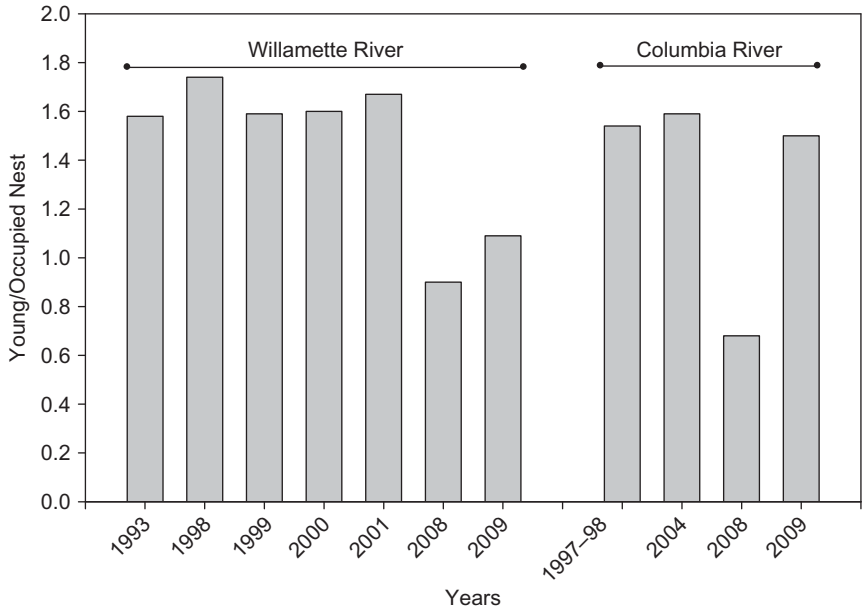

FIGURE 4. Productivity at ospreys nests with no eggs collected (young/occupied nest) in the 1990s and 2000s along the Willamette River, Oregon, and Columbia River, Oregon and Washington (Henny et al., 2009a; Henny et al., 2008a).

Note: Productivity at Willamette River nests represents the Upper River in 1993 (only location where pairs nested) and 2009 (River Mile 68–178, the only location studied); other years represent total river. Productivity at Columbia River nests in 1997/1998 and 2004 was determined between River Mile 29–286, while in 2008 and 2009 productivity was determined between River Mile 75–114 and 56–142.

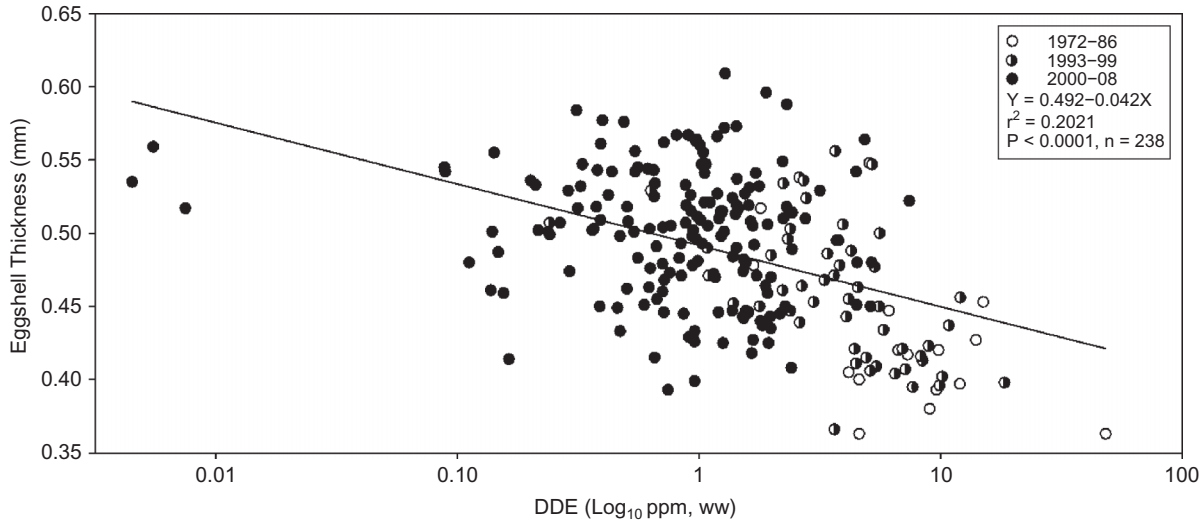

FIGURE 5. Semi-log relationship between DDE (ppm) and eggshell thickness (mm) using osprey eggs collected from the Pacific Northwest (OR, WA, ID), 1972–2008.

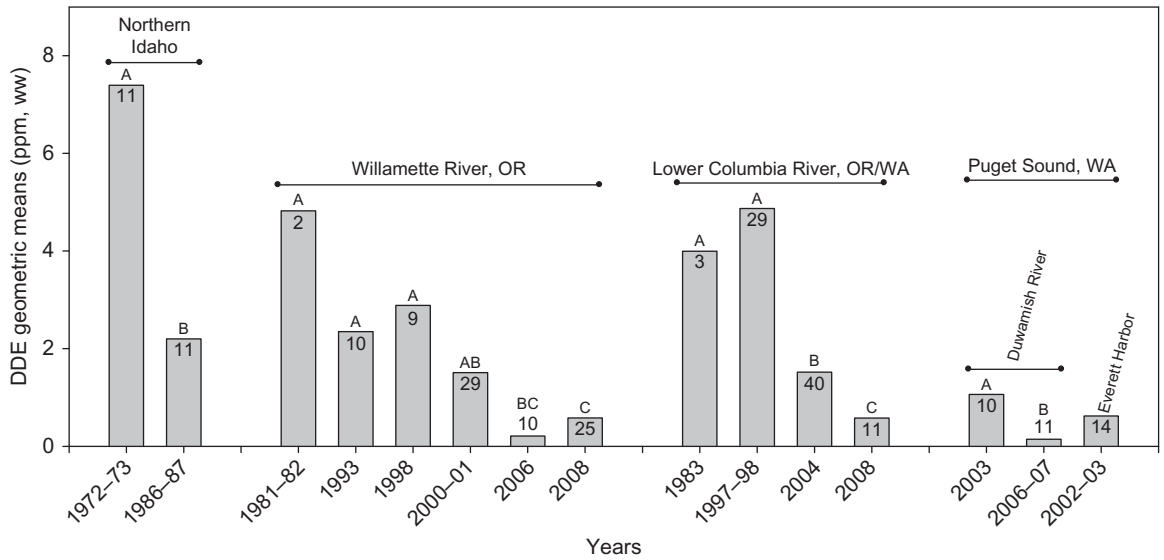

FIGURE 6. Geometric mean DDE concentrations (ppm, ww) in osprey eggs from the Pacific Northwest from 1972 to 2008.

Note: Bars sharing a letter for a location were not significantly different ($p > .05$). Numbers refer to eggs collected. Willamette River eggs collected in 1981–1982, 1993, and 2006 represent upper Willamette River only, where DDE residues were generally lower; other years represent total river. Columbia River eggs collected in 2008 from River Mile 71–114; other years represent total river.

increased from 78 in 1993 to 151 in 1998 (13.2% annual rate of rise) to 177 in 1999 (15.9%), to 202 in 2000 (13.2%), 234 in 2001 (14.7%), and 275 in 2008 (2.3%) (Figure 7).

The lower Columbia River nesting population continued to increase from 1997 (94 occupied nests) to 1998 (103 occupied nests) to 2004 (225 occupied nests) at annual rates of 9.6% and 13.0% (Henny et al., 2008a). Associated with the population elevations were higher reproductive rates in 2004 than in 1997/1998 and declines in geometric mean DDE egg concentrations from 4.9 ppm (ww) in 1997/1998 to 1.5 ppm in 2004. But perhaps most important, 24% of the eggs sampled in 1997/98 contained ≥8.0 ppm DDE, while by

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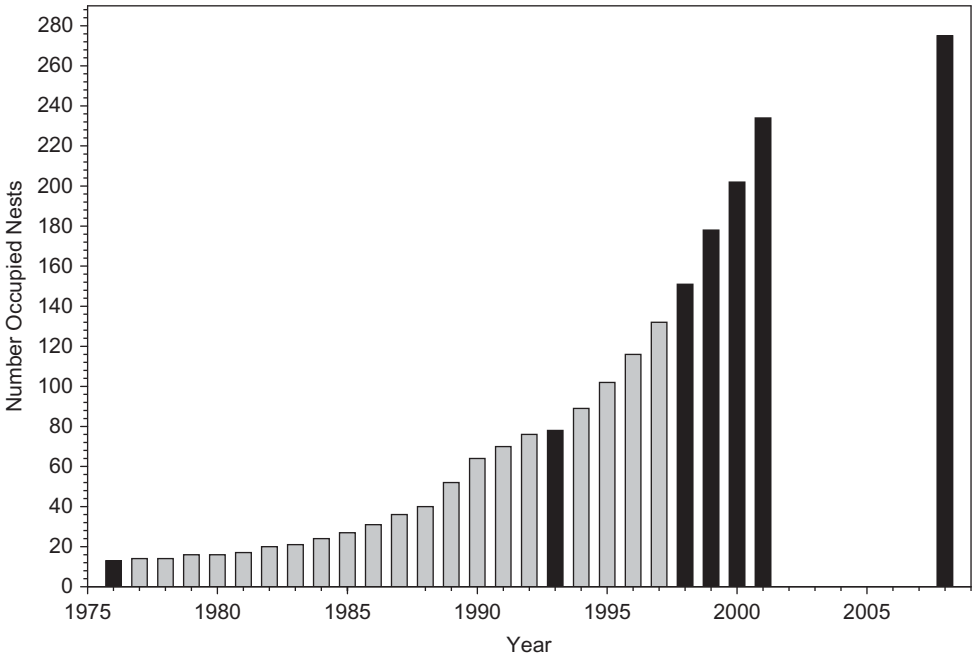

FIGURE 7. Number of occupied osprey nests along the Willamette River study area, 1976–2008. Black bars represent observed numbers and gray bars estimated numbers (for details see Henny et al., 2009a).

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2004 no eggs contained >2.29 ppm. Eggs from the osprey population nesting along the lower Columbia River in 1997/1998 contained the highest DDE concentrations reported in North America for the species during the late 1980s and 1990s, with correspondingly high DDE concentrations found in a key fish species in their diet, the large-scale sucker (*Catostomus macrocheilus*) (Henny et al., 2004). DDE-related reproductive effects were observed in a small portion of the Columbia River population through 1998, but perhaps only slowed the population growth rate through 2001 compared to the nearby Willamette River population where DDE residues were lower (Figure 6). Other contaminants (OC pesticides, PCB, PCDD, and PCDF) also decreased significantly in eggs between 1997/1998 and 2004 along the Columbia River, but mercury rose significantly (but still below effect concentrations). Similar changes in residue patterns and dramatic population increases were reported for the osprey populations along the Columbia River (225 occupied nests in 2004) and the Willamette River (234 in 2001), especially when compared to the <10 and 13 occupied nests in 1976. However, between 2001 (234 occupied nests) and 2008 (275) the annual rate of population increase along the Willamette River slowed markedly (2.3%). The recent slower growth rate coincided with the lower production (0.90 young/occupied nest) first observed in 2008 (no data for 2002–2007), and again in 2009 at 47 nests along the Upper Willamette River (1.09 young/occupied nest) (Figure 4). Productivity at 55 occupied nests along a portion of the Columbia River in 2008 was also low (0.68 young/occupied/nest), but productivity at 118 nests in 2009 improved (1.50 young/occupied nest). Both populations may be nearing carrying capacity.

U.S Nationwide Surveys, 1981, 1994, and 2001

The widespread studies of ospreys permitted the first estimate of the total nesting population in the United States in 1981 (Henny, 1983). The estimated approximately 8,000 breeding pairs were located in 5 regional populations (in order of abundance): Atlantic Coast, Florida and Gulf Coast, Pacific

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Northwest, Western Interior, and Great lakes. It is noteworthy that nesting populations had already increased by 1981 in the locations with low productivity in the 1950s, 1960s, and early 1970s. The nationwide survey was again conducted in 1994 (Houghton & Rymon, 1997) and, although summarized by slightly different regions, showed a 77.5% increase to approximately 14,200 nesting pairs. The nesting population more than doubled in the Western Region (101%) and the Mid- and South-Atlantic Coastal Region (110%). Other U.S. regions (Gulf and Florida, Great Lakes, and Northeast) showed population increases between 1981 and 1994 of 59%, 84%, and 94%, respectively. The large population increases reported throughout the osprey range in the United States by 1994 generally reduced concerns for the species, with studies at many locations terminated. Poole et al. (2002) conducted a similar polling of state agencies and others to estimate qualitatively the size of the osprey population in 2001. Using 1994 data for 5 missing states, the 2001 population in the contiguous continental United States was estimated at 16,000–19,000 pairs, representing an increase of roughly 25% over 1994 numbers.

Other Factors Potentially Contributing to Recent Osprey Increases (United States)

The population increases in all regions of the United States following the DDT ban in 1972 initially seem to imply that all populations were adversely affected to some degree during the late 1940s, 1950s, 1960s, and early 1970s, although limited/anecdotal or no historical data, especially from the late 1940s and 1950s, were available for many regions to show early population numbers or reduced reproductive rates. However, to simply conclude that all of the recent increases (recovery) were a population response to earlier contaminant effects may not be uniformly appropriate. Several confounding factors may be operating.

Nest sites and bodies of water with vulnerable fish populations (swimming near surface) are two critical needs for ospreys to be present and to thrive. Changes in fish resources available to osprey have changed over the last 40 years in Chesapeake Bay, including shifts in taxonomic and trophic structure of resident and migratory fish (Viverette et al., 2007). Substantial recent changes have occurred in osprey nesting locations, especially in the West, including use of relatively new reservoirs in Oregon (47% of nesting population in 1976) and California (20% of nesting population in 1975) (Henny et al., 1978a, 1978b). In addition, a relatively recent (1970s) switch also occurred in the western United States to nesting on artificial structures (power poles, platforms, etc.) instead of trees. In 1975 in northern California, 92% of nests ($n = 355$) were in trees, while in 1976 in Oregon, 95% of nests ($n = 308$) were in trees (Henny et al., 1978a, 1978b). Nearly all nests on artificial structures at that time in California and Oregon were located on nesting platforms specifically constructed for ospreys. The first artificial nest site (a power pole) used along the Willamette River was reported in 1977, but by 1999–2001 only 21–22% of nests for this increasing population nested in trees, and by 2008 only 12% (Table 2). Throughout the United States, significantly more young have been produced per nesting attempt at artificial sites compared to natural sites (Poole, 1989). This in part results from trees that are generally less stable than artificial sites, and nests more likely to blow down. Expansion of suitable habitat (reservoirs) and enhanced use of artificial nest sites confounds a simple conclusion that recent population increases were solely a recovery

TABLE 2. Nest Structures Used by Ospreys on Willamette River, Oregon

Year	Trees	Misc.[a]	Total
1976	13 (100%)	0	13
1993	12 (15%)	66 (85%)	78
1999	37 (21%)	140 (79%)	177
2000	45 (22%)	157 (78%)	202
2001	52 (22%)	182 (78%)	234
2008	33 (12%)	242 (88%)	275

[a]Miscellaneous includes power poles and towers, nesting platforms, pilings, cell towers, or bridges.

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from earlier contaminant exposure. Recent use of reservoirs may not be as important in all regions, but is especially important in the western United States, and perhaps in other localized areas.

In contrast to the western United States, osprey use of artificial nesting structures in the eastern United States was first reported 175 years ago. Audubon (1839, p. 363) mentioned in a letter to William MacGillivray in 1835 that an osprey nested on the roof of a house in the Florida Keys. The earliest record of an osprey nesting on a channel marker was in New York Harbor (Anonymous, 1881), though all of about 50 nests reported in Virginia by Bailey (1876) were in trees. Abbott (1911) included photographs of a nest on a telegraph pole and a fence, presumably on or near Gardiner's Island, New York. From 1911 to 1931, Miller (in Stone 1937) recorded 56 nest sites in Cape May County, New Jersey, with 53 (95%) in either live or dead trees; the others were on cartwheel poles (the original constructed osprey nesting platform). Smith (1931) reported that 16 of 17 nest sites (94%) were in trees in coastal Maryland in 1926. Although Abbott (1911), Stone (1937), and Bent (1937) recorded observations of ospreys nesting on boat houses, telegraph poles, fences, chimneys, and cartwheels on poles, the percentage on artificial structures at that time must have been small (unusual nest sites were probably highlighted in their books), but the transition to nesting on artificial structures started much earlier in the eastern United States compared to the western United States. By 1973, the estimated 1,450 osprey pairs nesting in Chesapeake Bay included only 32% nesting in trees (Henny et al., 1974), but when the estimated population rose to 3,473 pairs in 1995–1996, the proportion nesting in trees decreased to 7% (Watts et al., 2004). Similarly, in coastal New Jersey, Delaware, Maryland, and Virginia by 1975, trees accounted for only 27% of the nests (Henny et al., 1977). The construction of osprey nests on artificial structures seems associated with the timing and magnitude of human development near water, with such development much later in the western United States.

Other Factors Potentially Contributing to Recent Osprey Increases (Mexico)

A long-term osprey study (1977, 1992/1993 [portions surveyed in two different years], and 2006) in northwestern Mexico (Baja California, Gulf of California Islands, Sonora, and Sinaloa) typifies the complications of fully understanding causes of osprey population changes (Henny et al., 2008b). The nesting population in the survey area increased from an estimated 810 nesting pairs in 1977 to 1,362 pairs in 1992/1993, and then stabilized at 1,343 pairs in 2006. The overall pattern of increase between 1977 and 1992/1993 initially indicated findings reminiscent of United States surveys between 1981 and 1994. Based upon a more careful examination of the data, it became clear that the portion of the Baja California population nesting along the Gulf of California coast remained relatively stable during the three survey periods (255, 236, and 252 breeding pairs), while the population nesting along coastal Sinaloa, where earlier exposure to agricultural pesticides would be most likely suspected, showed a unique pattern with perhaps a post-DDT era population increase (70, 180, and 285 breeding pairs). Unfortunately, osprey eggs were never analyzed from coastal Sinaloa to verify earlier DDT exposure, and no pre-1977 population data exist. A few osprey eggs were collected along the Gulf of California side of Baja California in 1968, 1971, and 1972 (Spitzer et al., 1977; Henny & Anderson, 1979). Eggshell thinning was minimal (about 2–4%) with DDE residues generally low, which lends additional support to a lack of DDT effects there between 1977 and 2006, and to the concept of a relatively stable population over the three decade study, although localized population changes certainly existed. Thus, osprey population responses over time among large population segments in Mexico were variable, and probably similar to population segment responses in the United States.

The importance of artificial structures used for osprey nest sites radically changed recently in Mexico, from 4.3% in 1977, to 6.2% in 1992/1993, to 26.4% in 2006 (Table 3).

TABLE 3. Nest Structures Used by Ospreys in Baja California, Sea of Cortez, Sonora, and Sinaloa, Mexico

Year	Cliffs	Cacti	Ground	Trees	Misc.[a]	Total
1977	479 (59%)	213 (26%)	59 (7%)	24 (3%)	35 (4%)	810
1992/93	542 (40%)	506 (37%)	213 (16%)	16 (1%)	85 (6%)	1,362
2006	515 (38%)	436 (32%)	21 (2%)	17 (1%)	354 (26%)	1,343

Note. Adapted from Henny et al. (2008b).
[a]Includes power poles and towers, pilings, channel markers, boats (sunk and aground), road signs, etc.

However, the large osprey population increase in coastal Sinaloa was not associated with an increased use of artificial structures, because only 3.7% nested on them in 2006 (Henny et al., 2008b).

EMERGING CONTAMINANT ISSUES IN THE 21ST CENTURY

Many of the contaminants of concern today persist in the environment, resist environmental or metabolic breakdown, are lipophilic, and may bioaccumulate and/or biomagnify up the food web. As mentioned earlier, OC insecticide, PCB, PCDD, and PCDF concentrations in osprey eggs decreased by the end of the 20th century with limited or no continuing effects noted, except perhaps in a few localized areas. Thus, the osprey as a species provides a means of evaluating emerging contaminants with limited potential for confounding effects from the legacy group of contaminants.

PBDE and hexabromocyclododecane are widely used as flame retardants in thermoplastics, textiles, polyurethane foams, and electronic circuitry. PBDE persist in the environment, and bioaccumulate and biomagnify up the aquatic food web to the top predatory fish, mammal, and bird species in many ecosystems (de Wit, 2002). In addition to many other species of birds of prey, PBDE residues were detected in ospreys from Sweden (Jansson et al., 1993), Norway (Herzke et al., 2005), British Columbia, Canada (Elliott et al., 2005), and Delaware, Maryland, Virginia, Oregon, and Washington (Rattner et al., 2004; Toschik et al., 2005; Henny et al., 2009b). In contrast to the legacy contaminants, PBDE increased in biota since the 1970s, and were reported in all 120 osprey eggs analyzed from Oregon and Washington between 2002 and 2007 (Henny et al., 2009b); PBDE concentrations rose in osprey eggs over time at two northwest locations (Seattle, WA, and Columbia River, River Mile 29–84) where temporal patterns could be evaluated. Furthermore, the ΣPBDE concentrations in some Oregon and Washington osprey eggs at two sites in 2006 and 2007 exceeded 1,000 ppb ww, with significant negative relationships indicated at both locations between productivity and ΣPBDE concentrations in eggs. The number of nests represented by eggs with concentrations >1,000 ppb was limited; thus, the 1,000-ppb effect level must be regarded as tentative.

Current-use chlorophenoxy herbicides including 2,4-dichlorophenoxyacetic acid, dicamba, triclopyr, dicamba, dimethyl tetrachloroterphthalate (DCPA or dacthal) and the metabolite of pyrethroids, 3-phenoxybenzoic acid (3-PBA), and the fungicide chlorothalonil were investigated in the eggs of ospreys collected at 15 nests in Puget Sound, Washington (Chu et al., 2007). Dacthal was quantified in six eggs; however, an unexpected DCPA structural isomer, dimethyl tetrachlorophthalate (diMe-TCP), was quantified in eggs from all sites. As diMe-TCP is not an industrial product, and was not commercially available, its source is unclear. The fungicide chlorothalonil was detectable in five eggs, but was not quantifiable. These findings indicate that DCPA and diMe-TCP can accumulate in the food web of fish-eating ospreys and be transferred in ovo to eggs, and thus may be of concern to the developing chick and general reproductive health of osprey populations.

Perfluorinated acids and sulfonate compounds (PFC) were evaluated in osprey eggs

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collected in Chesapeake Bay, the Delaware River, Delaware Bay, and Casco Bay, Maine, from the eastern United States (Rattner et al., 2004; Toschik et al., 2005; Goodale 2010). These compounds were used for decades to make commercial products resistant to heat, oil, grease, stains, and water, such as carpets, fabrics, fire-fighting foam, and nonstick cookware. In addition to perfluorooctane sulfonates (PFOS) reported in osprey eggs from the eastern United States, PFCs were also found in osprey eggs collected along the lower Columbia River near Portland, OR, in 2008 (Furl and Meredith 2010). Little is known about the toxicity of perfluorinated compounds to birds.

The presence of dacthal isomers, chlorothalonil, brominated flame retardants, and PFOS in eggs from Oregon and Washington indicates that ospreys are constantly being exposed to an increasingly complex profile of bioaccumulative contaminants. More recently, pharmaceuticals and personal care products were found in a variety of aquatic environments, including fish (Ramirez et al., 2009), raising concerns about their potential for accumulation and effects. New techniques are being developed to identify and quantify these emerging contaminants, e.g., the determination of alkylphenol and alkylphonolethoxylates in osprey eggs from Chesapeake Bay (Schmitz-Alfonzo et al., 2003). Continued research evaluating potential emerging contaminants, food web dynamics and ecotoxicological implications of such environmental exposures is warranted. However, among legacy contaminants, mercury is a notable exception that has not decreased over time in osprey eggs from the lower Columbia River (Henny et al., 2008a).

OSPREY ROLE AS WORLDWIDE SENTINEL SPECIES

For a species to be considered a key "sentinel species" for contaminant investigations, theoretically it needs to meet a series of requirements recently reviewed by Grove et al. (2009), which include: (1) widespread distribution, (2) nonmigratory status, (3) position at top of aquatic food web, (4) ability to bioaccumulate contaminants, (5) restricted home range, (6) well-known biology and natural history, (7) sensitivity to contaminants, (8) available in sufficient numbers, and (9) be maintained and studied in captivity.

Few, if any, species meet all of these criteria, with the osprey clearly meeting seven of the nine (Grove et al., 2009). However, in portions of its range including the northern latitudes of North America, it is clearly migratory and away from its breeding area for about 6 mo of the year. Migration has the potential to confound contaminant studies on the nesting grounds with additional sources of exposure on the wintering grounds. To address this issue, adult female ospreys from Oregon, Washington, and British Columbia, with an egg collected from each nest for residue analysis, were fitted with satellite transmitters to determine wintering localities. Then fish were sampled on the breeding grounds and wintering grounds (Elliott et al., 2007). Ospreys spend about 1 mo on the breeding grounds before laying eggs, and contaminants in eggs were best correlated with concentrations in fish on the breeding grounds and not fish on the wintering grounds. This conclusion was also supported by localized studies on the breeding grounds, e.g., above and below contaminant point sources along rivers and estuaries (higher residue concentrations downstream of point sources). Thus, although the species is migratory, that trait does not limit its usefulness as a sentinel species. Another potential limitation is the fact that it cannot be maintained and studied in the laboratory. Controlled laboratory studies are important for determining causation, dose-response relationships, and molecular mechanisms of action, usually from single-chemical exposures. However, osprey eggs have been taken into the laboratory and hatched in incubators, and evaluated for biochemical responses, histopathology, and other physiological parameters (e.g., P4501A, vitamin A), with a number of parameters correlated with residual yolk sac contaminant concentrations (Elliott et al., 2001). Thus, the primary

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limitation is the inability to conduct laboratory dose-response studies.

Positives for the species include:

1. Widespread distribution—It is most exciting and useful for researchers and the public to see residue data for the same species from many parts of the world, e.g., direct comparisons—Columbia River versus Chesapeake Bay, Volga River, Russia, versus Baja California, Mexico—with no need to interpolate from species to species occupying different niches.
2. Top of aquatic avian food web—The osprey is essentially an obligate piscivore, and the top avian predator in most settings where ospreys occur except that they sometimes share the role with bald eagles, which have a broader diet (not all fish).
3. Bioaccumulate many lipophilic contaminants—Numerous studies were conducted regarding the sensitivity to many legacy contaminants. The accumulation of several emerging contaminants was recently reported, including PBDE, PFOS, dacthal, chlorothalonil, alkylphenol, and alkylphenolethoxylates.
4. Restricted home range—Ospreys generally forage within 1–3 km of nest sites, with some foraging examples at greater distances to take advantage of specific fish runs.
5. Well-known biology and natural history—The decline of the osprey along the Atlantic Coast led to many studies starting nationwide in the 1960s, with much learned about the species over the last 40 years.
6. Sensitivity to contaminants—Legacy contaminant sensitivity is well understood, including to OC, PCB, PCDD, PCDF, and mercury, with studies underway to understand emerging contaminants.
7. Available in sufficient numbers for field studies–Populations at most locations have recovered from DDT-era problems, and now can again play the role of a sentinel species.

Further evaluation of osprey life history traits that make it a sentinel species of choice are:

1. An aquatic diet of 99+% fish (often one dominant fish species at a location such as suckers important in Columbia and Willamette Rivers (Johnson et al., 2008) with residue concentrations in osprey eggs primarily dependent upon fish on the breeding grounds.
2. Localized feeding habits, usually within short distance of nest. Fish species captured can be determined from prey remains at nests, direct observations, and/or photographs.
3. Long-lived species, up to 25 years; strong nest site fidelity and returns year after year to the same or nearby nest, which is readily observable and easily detected from aerial/ground/boat surveys. Many now nest on artificial structures, which often facilitate access, including ladders on Coast Guard channel markers.
4. Adapts to nesting in human landscapes, including industrial and municipal sites where contamination may be more severe, and readily habituates to human activity. This association with human activity sometimes results in conflicts with owners of nest site structures (electric utility companies and cell tower companies).
5. Tolerates short-term nest disturbance for egg/blood collection, resulting in little or no effect on nest success. (Note: early visits to bald eagle nests to collect egg produced a high rate of nest abandonment.)
6. Removal of "sample egg" from usual 3-egg clutch for contaminant study exerted limited effect on productivity at nest, i.e., loss of 0.28 young fledged for each egg collected (Henny et al., 2004).
7. Nests spatially distributed at regular intervals along waterways, as opposed to clumped at a limited number of regional colonies. This distribution permits random egg and tissue collections along river segments or strategic collections related to potential contaminant sources.

Based upon these positive characteristics, ospreys along the Willamette River were examined to determine population size and

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distribution, reproductive rates, food habits, and biomagnification factors (BMF) for various contaminants from fish to osprey eggs (Henny et al., 2009a). Empirical estimates of BMF require food habits information, residues in fish species, and contaminants in osprey eggs. Data permit more realistic "risk assessments"; for example, if you know contaminant concentrations in the fish living in the area and the percentage of each species in the diet (prior to egg laying), egg concentrations can be estimated. For example, DDE in fish in the diet is magnified by an estimated 87-fold to the osprey egg, while $\sum$PCBs magnified by a factor of 11-fold. BMF information for emerging lipophilic contaminants is still needed. More studies are underway with emerging contaminants to better understand trends and possible effects on osprey reproduction and blood parameters in young.

CONCLUSIONS

Many North American osprey populations were adversely impacted by DDT and perhaps other contaminants from the late 1940s to at least the early 1970s; some individual pairs continued to have reproductive problems into the late 1990s. After the plight of the osprey first came into focus in 1964, nearly every population in North America was studied. Reproductive success, the weak link in the life cycle, the associated eggshell thickness, and population changes over time were the focus of the studies, which compared observed reproductive rates with the estimated standard (later refined to 0.80 young/nesting attempt). It was apparent by the early 1970s that those populations with relatively long-term data sets and below-normal reproductive rates in the 1960s were showing improved reproductive rates, although the populations were not yet increasing. The improvement was associated with the reduced use of DDT and its eventual ban in 1972. By 1981 and again in 1994 and 2001, total population estimates for the United States showed increases from 8,000 pairs to 14,200 pairs to 16,000–19,000 pairs. The population increases occurred at different rates in different regions, which could imply different levels of contaminant exposure among the populations; the limited egg residue data at least partially support that concept. However, increased use of artificial nest sites (especially in the Western region) beginning in the 1970s and exploitation of relatively new reservoirs probably accounted for some of the population rise. At least one population (Gulf of California coast of Baja California, Mexico), with limited contaminant exposure, remained relatively stable at apparent carrying capacity for the last 30 years. Other local populations may also fit this pattern. Thus, recent large population increases may not always indicate that the population was severely affected earlier by contaminants—other factors may have recently enhanced the carrying capacity of a locality. Although most populations increased dramatically in recent years (although often at different rates), it is noteworthy that the lower Columbia River still had a portion of the population with DDE-associated reduced reproductive success in 1997/1998. The Columbia River drains a large agriculture and forest area, with osprey eggs containing the highest DDE concentrations in North America in the late 1980s and 1990s. Furthermore, the osprey population there was decimated by the mid-1970s. This population rapidly rose in the 1990s, and DDE was no longer an osprey issue in the lower Columbia River by 2004. The rapid population growth phase also occurred along the Willamette River in the 1990s, but is no longer occurring; the population in the 2000s appears to be reaching carrying capacity and stabilizing like many other osprey populations. The total population along the Columbia River has not been studied since 2004.

As a top predator, the osprey has been studied at several locations to evaluate emerging contaminants including PBDE, PFOS, dacthal, chlorothalonil, alkylphenol, and alkylphonolethoxylates. Studies of these emerging contaminants with ospreys are important because, with few exceptions, there are no longer confounding effects occurring from legacy contaminants. With much basic and applied research conducted on ospreys over the last

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45 years, many advantages are readily apparent for using them as a sentinel species for future contaminant studies. An important point here is that most populations in North America have been studied with at least population numbers and often production rates reported at some point in time. In addition, ospreys are now generally abundant and well distributed worldwide. It might be useful to reevaluate the "production standard" for maintaining a stable population now that population numbers have greatly increased at most locations (higher nesting density), especially from the time of Spitzer's (1980) earlier work. There are some long-term data sets available to perhaps make such an evaluation. However, a key statistic needed is the age at first breeding (it is probably now delayed, Poole, 1989:147), which requires a marked population, good understanding of each pair/individual present, and long-term research efforts. This large, highly visible, fish-eating top predator is present in many North American watersheds, and has played a role in the past and should continue to play an important role in monitoring and assessing many, but understandably not all, emerging contaminants. The species will be best used to study persistent lipophilic contaminants that biomagnify up aquatic food webs.

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