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Using Raptors as Environmental Sentinels: Monitoring the White-tailed Sea Eagle *Haliaeetus albicilla* in Sweden

This paper summarizes results from the monitoring of reproduction of white-tailed sea eagle in Sweden 1965–2006. Since 1989 the eagle population on the Swedish Baltic coast has been included in the National Environment Monitoring Program as an indicator species for potentially harmful chemicals. The percentage of successfully reproducing pairs and nestling brood size decreased in synchrony with rising concentrations of contaminants in the 1950s on into the 1970s. Mean productivity was 1.3 young per pair prior to 1950 and decreased to 0.3 in 1965–1985. Dichlorodiphenyldichloroethene (DDE) in eagle eggs decreased from a range of annual means in 1965–1974 of 600-1200 μg g^{-1} (lipid weight) to 60–140 μg g^{-1} in 1996–2005. Total polychlorinated biphenyl (PCB) concentrations averaged above 1000 μg g^{-1} into the early 1980s and remained in the range of 250–500 μg g^{-1} in 1996–2005. Productivity began to improve when concentrations of DDE and PCBs dropped below approximately 300 and 800 μg g^{-1}, respectively. Brood size remains below the pre-1950 level in one coastal region, indicating a possible impact from other contaminants. The power to detect significant trends under the program is presented and discussed: if white-tailed sea eagle reproduction had been monitored earlier during the 20th century, the negative impact of dichlorodiphenyltrichloroethane (DDT, source of DDE) would have been signaled as early as the 1950s in the Baltic Sea. The dramatic fall of white-tailed sea eagle reproduction under the influence of DDT and PCBs, and the subsequent rise following their ban, illustrates the usefulness of raptors like sea eagles as sentinels for environmental pollutants.

Sea Eagle *Haliaeetus albicilla* nest with nestlings, Sweden (Photo: B. Helander).

INTRODUCTION

Raptors feeding at a high trophic level become exposed to persistent and potentially harmful pollutants. Those species exposed to the greatest concentrations have shown dramatic population declines during the 20th century, mainly as a result of contamination with pollutants (e.g., peregrine falcon *Falco peregrinus,* white-tailed sea eagle *Haliaeetus albicilla,* bald eagle *Haliaeetus leucocephalus*). Thus, raptors can serve as powerful sentinels for environmental monitoring. In Sweden, raptor populations are monitored in a few national “species projects” that focus primarily on breeding populations and their distributions and reproduction—white-tailed sea eagle (1), golden eagle *Aquila chrysaëtos* (2), peregrine falcon (3), gyrfalcon *Falco rusticolus* (4)—and by annual counts of migrants (5, 6). Regional or local surveys of breeding populations are also performed for a number of species, mainly on a private basis. In addition, series of data from the ringing of nestlings, administered by the Swedish Bird Ringing Centre, can be useful for monitoring populations.

In this paper the terms “white-tailed sea eagle” and “sea eagle” are used synonymously. We briefly present methods and results from the monitoring of white-tailed sea eagle reproduction on the Swedish Baltic Sea coast in relation to residue concentrations of dichlorodiphenyldichloroethylene (DDE) and polychlorinated biphenyls (PCBs) over 42 y. We also present data on the power of the monitoring program to detect significant linear trends and differences between samples. The sea eagle provided the earliest signal that harmful chemicals had reached alarming concentrations in the Baltic Sea. In 1964, annual monitoring of the breeding population on the Baltic coast began and from 1989 was adopted into the National Environment Monitoring Programme under the Swedish Environmental Protection Agency (7). Justifications for using the sea eagle as an indicator in a national environmental monitoring program include that it feeds at the very top of the food chain, that it has the highest concentrations of persistent pollutants measured in the Baltic, and that its reproduction is strongly affected by contaminants. Data from an isolated and far less contaminated population in Swedish Lapland are presented for comparison. Residue concentrations of selected organochlorines in eggs from five raptor species in Sweden are summarized in Table 1.

MATERIALS AND METHODS

In addition to being highly exposed to persistent chemicals, the sea eagle has other features that are favorable from a monitoring perspective. Territorial adults on the Baltic Sea coast are mainly sedentary and thus reflect the regional contaminant situation. Mates of pairs are generally faithful to each other and to their breeding sites, and the sites are commonly used over many generations of eagles, providing good opportunities for long-term studies. Of particular value, a large portion of the breeders is currently ringed, improving the possibilities for study of individual birds over time.

Table 1. Residue concentrations in $\mu g\ g^{-1}$ lipid weight of sum of sDDT, total PCB, and polybrominated diphenylethers (PBD) in eggs from selected raptor species in Sweden. n = number of clutches; (na) = not analyzed. Contaminant data for sea eagle from Helander et al. (8, 9), peregrine falcon from Lindberg et al. (10, 11, and unpubl. data), osprey *Pandion haliaetus* from Odsjö and Sondell (12), marsh harrier (*Circus aeruginosus*) from Odsjö and Sondell (13) and golden eagle from Lindberg (unpubl. data).

	1965–1980			1990–2002				
Species, location	sDDT*	PCBs	n	sDDT*	PCB	n	PBD†	n
White-tailed sea eagle, Baltic Sea	825	1130	34	120	440	54	4.7	20
White-tailed sea eagle, Lapland	186	275	4	17	60	21	0.94	12
Peregrine falcon, S Sweden	360	792	24				3.8	24
Peregrine falcon, N Sweden	337	515	15	58‡	240‡	9	4.5	18
Osprey, S and N Sweden	184	178	111	(na)	(na)		(na)	
Marsh harrier	366	533	70	(na)	(na)		(na)	
Golden eagle, N Sweden	(na)	(na)		3.7	5.6	14	0.068	14

* Almost all DDE. † BDE 47, 99, 100, 153, 154, 183, 209. ‡ S and N Sweden.

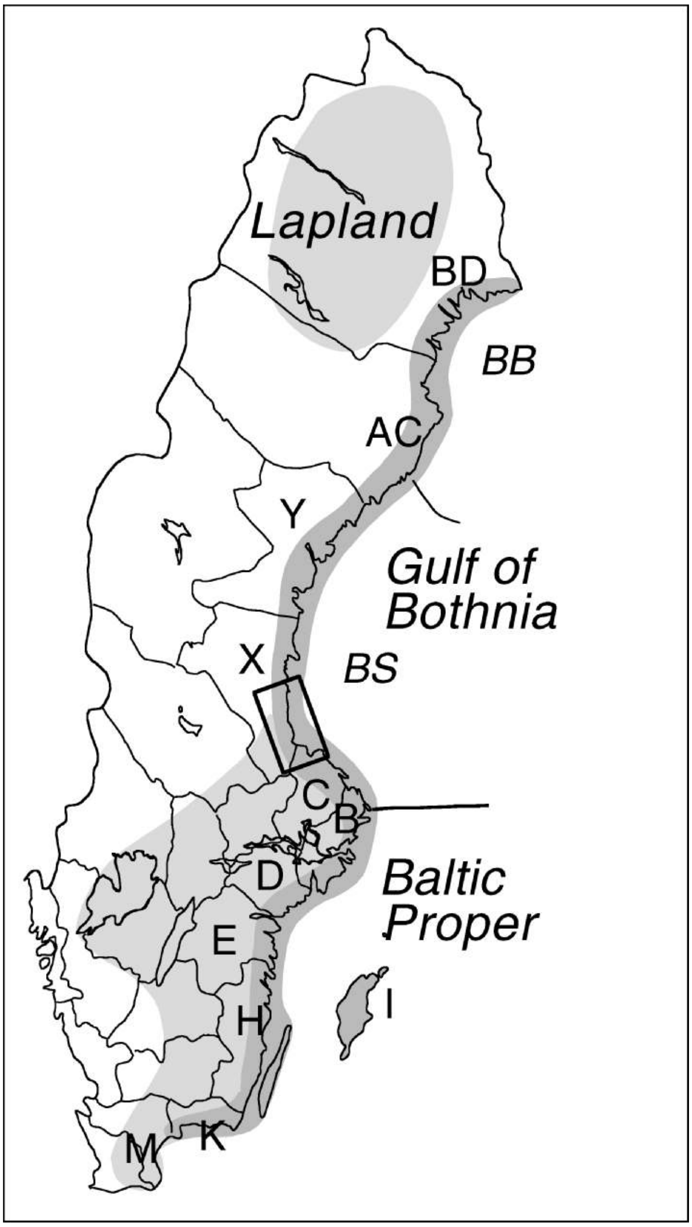

Figure 1. Distribution of white-tailed sea eagle in Sweden, 2006. Study areas in this paper comprise the population on the coast (darker) and the northern inland population (Lapland). BS = Bothnian Sea, BB = Bothnian Bay (BS and BB together comprise the Gulf of Bothnia). Letter codes for coastal counties are given for reference. The rectangle indicates a study area in the southern Bothnian Sea.

Nest Checks and Reproductive Parameters

Study areas are outlined in Figure 1. Two surveys are performed each season on the Baltic coast, in order to obtain reliable data on breeding success (14, 15). Breeding sites are first checked during incubation in March–April to confirm occupancy (7). This is done either from a helicopter, or from a safe distance on the ground. All occupied nests are revisited on foot and climbed to, from mid-May to mid-June when nestlings are expected to be 4–8 wk old. In Lapland, all known nest sites are surveyed by helicopter and thus inspected from above during the nestling period, and nests containing young or dead eggs are climbed to. In all regions, the monitoring of reproduction focuses on the annual distribution of nests producing no, one, two, and three nestlings (three being the maximum number of offspring in this species). From these frequency distributions, two robust parameters are calculated: the proportion of reproducing pairs, denoted as "breeding success," and the mean number of >4 wk old nestlings, denoted as "brood size." For reference, records on breeding success and brood size over the study period are compared with previously derived background levels from carefully selected historical records (7, 16). "Productivity" denotes the total number of nestlings produced divided by the total number of occupied territories checked in a year (i.e., includes nonproductive pairs). Sample sizes increased over the study period as populations were growing—from a total of about 30 to 260 checked pairs per year on the Baltic coast from 1965 to 2006 and from 12 to 60 in Lapland from 1976 to 2006.

Sampling

All accessible nestlings are color-ringed (17) and have five upper wing coverts collected. A blood sample (up to 10 ml depending on nestling size) is drawn from the brachial vein using sterile techniques, usually from one nestling of each brood. Each blood sample is partitioned directly upon sampling: two subsamples of 0.5 ml, for genetic studies, are each mixed with 0.5 ml of ethylenediaminetetraacetic acid standard saline citrate solution in preprepared 5-ml cryogenic vials; the remaining part of the sample is transferred to 5-ml cryogenic vials, for spinning and partitioning of plasma and red cells by the end of the day. Vials are individually labeled on each sampling occasion. The vials are carried in an ice-box for cooling in the field, and the samples are transferred to liquid nitrogen after the preparation is completed each day. Blood and feather samples have been archived for special research projects (18, 19). Nestlings are weighed on a 10-kg Pesola spring balance, and correction is made for the estimated weight of crop content. Measurements are taken of wing length (maximum chord), tarsus width, and tarsus depth (20). Dead eggs, shell fragments, and shed feathers

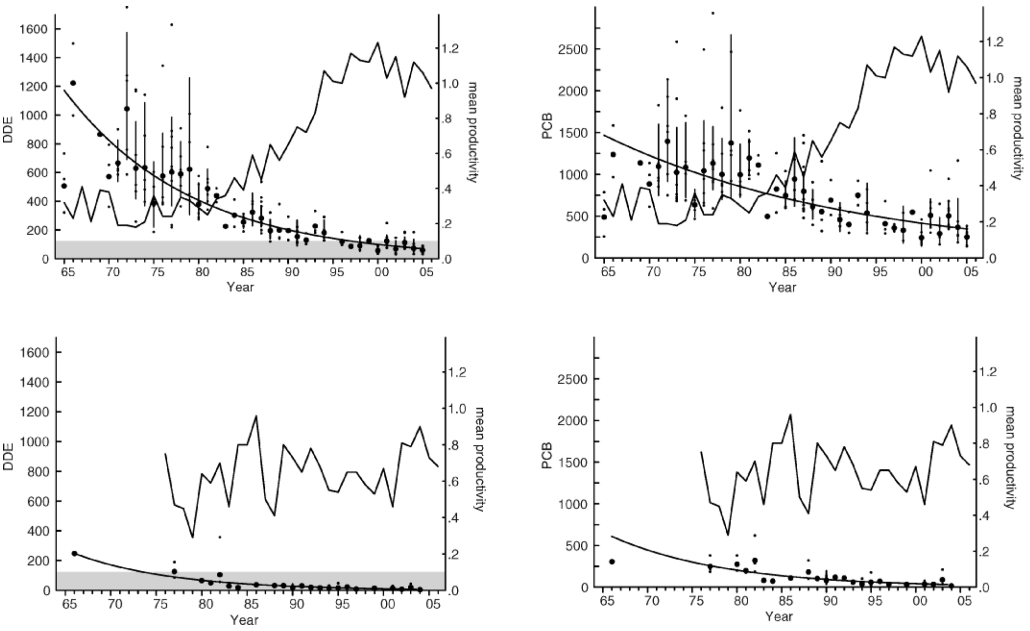

Figure 2. Mean annual productivity and residue concentrations of DDE and total PCB in white-tailed sea eagle eggs, Swedish Baltic coast 1965–2005 (upper graphs) and Swedish Lapland 1976–2005. Areas below a previously estimated LOEL for DDE (9) are shaded. Large dots = annual geometric means, small dots = individual clutches, vertical lines = 95% confidence limits (for sample sizes >3). Regression lines for DDE and PCB in the eggs decreased significantly during the study periods ($p < 0.001$). Productivity of the coastal population increased significantly ($p < 0.001$); there was no statistically significant change in productivity over the study period in Lapland.

of the adult birds are collected from all visited successful as well as unsuccessful nests.

Chemical Analyses

Chemical analyses of DDTs and PCBs in egg samples have been performed by the Department of Applied Environmental Science (ITM), Stockholm University, according to published protocols (21). Previous tentative studies of dieldrin, hexachlorobenzene, and mercury revealed no significant relationships with reproduction at the concentrations present in eagle eggs of this population (8). The sum of DDTs present in the eggs was almost exclusively DDE, and a sum concentration was not calculated here. Before 1991, "total PCB" concentrations were determined from packed column gas chromatography (22). From 1991, capillary column gas chromatography was applied (23). For comparability over the study period all PCB concentrations in sea eagle eggs are given as "total PCB," derived by multiplying CB-138 with a correction factor calculated from the relationship between CB-138 (from capillary column chromatography) and PCB peak 10 (from packed column chromatography), and between PCB peak 10 and total PCB (9). Eggs collected after the incubation period can vary greatly in degree of desiccation, which needs to be corrected for if residue concentrations are to be given on a wet weight basis; this can be done based on measured, or calculated, volume of each egg (24). Some eggs in this study were crushed, and proper estimates of volume could then not be attained. Residue concentrations are here given on a lipid weight basis as $\mu g\ g^{-1}$. The eagle eggs contained on average 5.08% lipids (9), so residue concentrations on a lipid weight basis can be converted to a wet weight basis multiplying with a factor 0.05. Only eggs with no or small embryos (<75 mm) were included, to avoid an influence on residue concentrations from metabolism of lipids (9, 25, 26). Arithmetic mean values were used for clutches represented by more than one egg.

Statistical Tests

Simple log-linear regression analysis has been carried out to investigate average changes over time. To check for significant nonlinear trend components, a LOESS smoother (27) was applied and an analysis of variance was used to check whether the smoother explained significantly more than the regression line according to a method suggested by Nicholson, Fryer, and Larsen (28). Statistical power analyses (29, 30) were used to estimate the minimum annual trend likely to be detected at a statistical power of 80% during a monitoring period of 10 y (31). To investigate the possible effect of a future reduced sampling scheme, repeated random sampling (5000 times) from 1991 to 2006 in the current database was carried out, simulating a maximum of 50, 25, 20, 15, and 10 records each year. Contingency analysis, using the G-test with Williams correction, a log-likelihood ratio test (32), was applied for comparisons between geographical regions and time periods.

RESULTS AND DISCUSSION

Productivity versus DDE and PCBs over Time

Changes in productivity and concentrations of DDE and PCBs in eggs of sea eagles over the study period are shown in Figure 2. Productivity of the coastal population began to improve in the 1980s and leveled off in the late 1990s. Annual means of DDE decreased from a range of 600-1200 $\mu g\ g^{-1}$ in the 1960s and early 1970s to a range of 60–140 $\mu g\ g^{-1}$ by the end of the study period (n = 180 clutches). Annual mean concentrations of PCBs stayed above 1000 $\mu g\ g^{-1}$ into the early 1980s and remained in the range 250–500 $\mu g\ g^{-1}$ from 1996 through 2005. The productivity in Lapland showed large annual variations with no significant trend over the period. Residue concentrations in the eagle eggs from Lapland were below 100 and 250 $\mu g\ g^{-1}$ for DDE and PCBs, respectively, over most of the study period (n = 43 clutches).

Figure 2 illustrates that the decrease of DDE and PCBs in collected sea eagle eggs and the improvement in productivity over the study period did not happen in synchrony. DDE concentrations decreased significantly—almost threefold from 1965 to 1980—but productivity did not really begin to improve until the mid-1980s, when the average residue concentrations in collected eggs fell below 300 $\mu g\ g^{-1}$ DDE and 800 $\mu g\ g^{-1}$ PCBs. Productivity stabilized near the background level from the mid-1990s as DDE in the eggs had decreased to about 120 $\mu g\ g^{-1}$, a previously estimated lowest observable effect level (LOEL) (9). Polychlorinated biphenyl concentrations in the eggs over the last 10 y averaged around 500 $\mu g\ g^{-1}$, which is a suggested LOEL for PCBs in this species (9). This implies that there may still be some effect from PCBs on reproduction. The strong

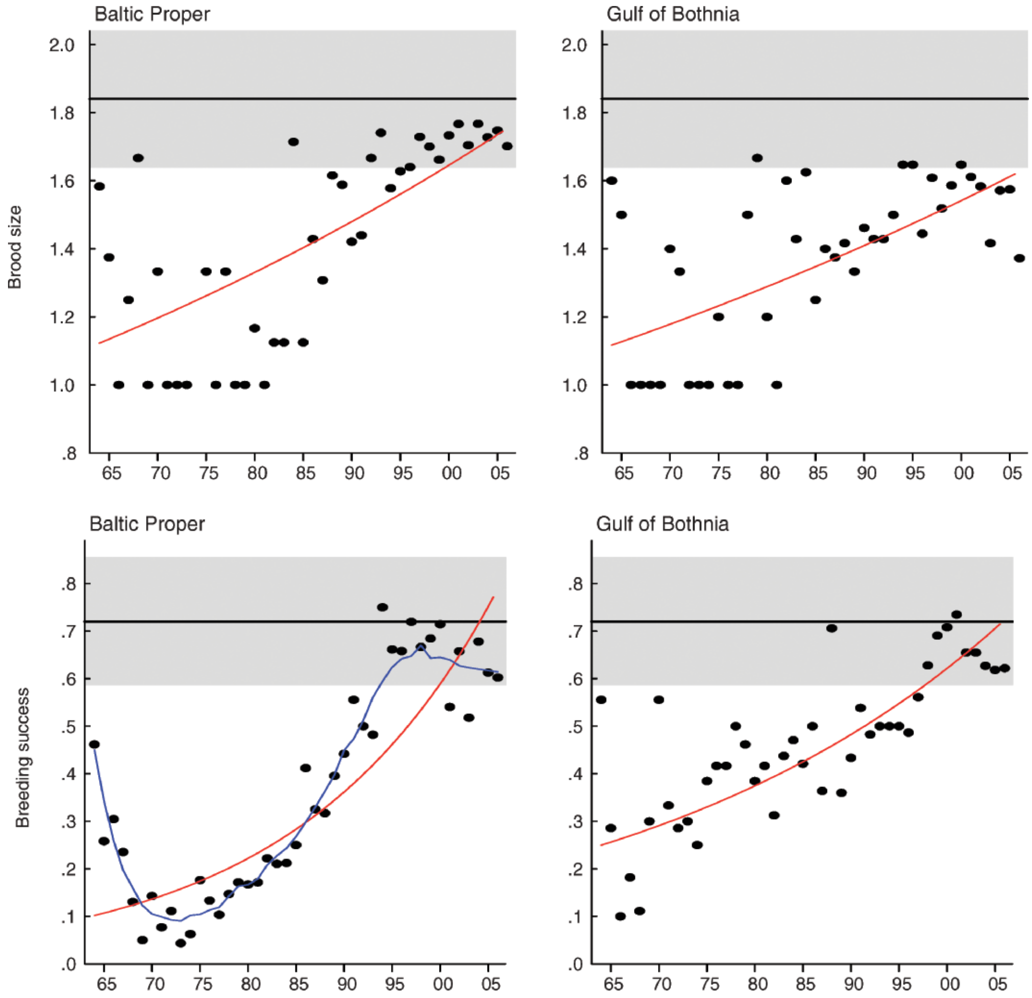

Figure 3. Breeding success and mean brood size in white-tailed sea eagle on the Swedish coast of the Gulf of Bothnia and the Baltic Proper, 1964–2006. Reference levels with 95% confidence limits are given according to (7). For the set of breeding success data from the Baltic Proper, the LOESS smoother explained significantly more than the regression line.

correlation between DDE and PCB concentrations in the eggs has complicated the interpretations of effect levels for PCBs.

Breeding Success and Brood Size

Breeding success and brood size of sea eagles on the northern and southern Baltic coast from 1965 to 2006 are presented in Figure 3. Along with the growth of the coastal population, the number of checked pairs per year increased from 20–30 before 1975 to 176 in 2006 in the Baltic Proper, and from around 10 before 1975 to 89 in 2006 in the Gulf of Bothnia. Breeding success dropped to its lowest level in the Baltic Proper in the mid-1970s and increased significantly in both areas from the early 1980s. By the middle to late 1990s, breeding success in both areas was no longer statistically different from the background level. Similarly, brood sizes began to increase in both areas from the 1980s; it reached the background level in the southern region in the late 1990s.

In the Gulf of Bothnia, however, brood size is still significantly below this reference level. This is mainly due to smaller broods in the southern part of the Bothnian Sea (Table 2). Is this a result of lower hatching success among laid eggs, or could it be a result of smaller clutches, e.g., due to food shortage? There are no indications of food shortage in the area, but empirical data are lacking both on food availability and clutch size for different regions—the latter is a result of a precautionary decision not to visit nests during incubation to avoid disturbance during a sensitive part of the breeding period for this species. However, an analysis of the distribution of successful nests containing dead eggs together with the young shows that the presence of dead eggs was about five times as frequent in nests in the rectangular study area in the southern Bothnian Sea (see Fig. 1), as compared with the rest of the Gulf of Bothnia and the Baltic Proper (Table 3). The difference is highly significant ($p < 0.001$). There was no significant

Table 2. Regional distribution of brood sizes of white-tailed sea eagle on the Swedish Baltic coast, 1996–2006. County codes refer to Figure 1; n = number of broods. Bold italics indicate brood sizes below the 95% confidence limits for background reference level (1.64–2.04).

County	Mean brood size	n
I	1.78	23
H	1.85	211
E	1.67	144
D	1.69	85
B	1.64	325
C	***1.57***	223
X	***1.38***	93
Y+AC	1.64	64

Table 3. Regional distribution of white-tailed sea eagle nests containing young and dead eggs, Swedish Baltic coast 1993–2006. n_1 = number of nests containing young and dead eggs; n_2 = total number of checked nests with young; n_1/n_2 = % with dead eggs.

Region	n_1	n_2	n_1/n_2
Baltic Proper	23	938	2.5
Southern Bothnian Sea	18	114	15.8***
Gulf of Bothnia north of region 2	12	305	3.9

*** $p < 0.001$.

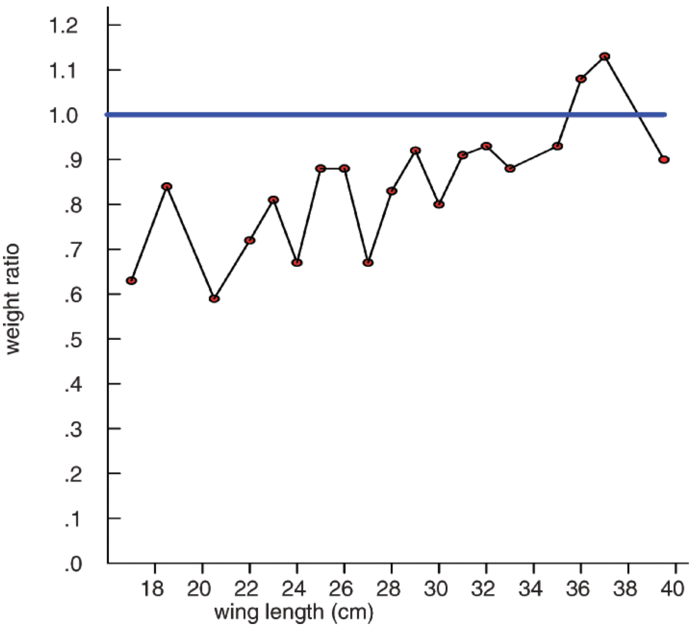

Figure 4. Weight ratio of nestlings from Lapland (n = 53) in relation to nestlings from the Baltic coast (n = 56, reference line 1.0) over ages 3.5–7 wk as indicated by wing length in cm.

difference between the areas in Table 3 in concentrations of DDE and PCBs in the eggs. A recent study on concentrations of brominated flame retardants (BFRs) in eggs showed no difference between these two regions (33). A possible influence from other contaminants on the hatchability of eggs in the study area in the southern Bothnian Sea is under investigation.

Body Mass

Body mass can be indicative of food stress and health and is usually easily obtained when handling nestlings. An age-dependant increment in body mass naturally takes place in growing nestlings, and comparison of weights between nestlings must therefore be based on specimens of the same age. Wing length is strongly correlated to age in sea eagle nestlings (34, 35) and can be used as a proxy for age. A subsample (all nestlings available from 1977 to 1982) illustrates a considerable difference in weight between nestlings from the Swedish Baltic coast and Lapland (Fig. 4). At 3.5–5 wk of age, Lapland nestlings in this sample weighed 22% less than Baltic nestlings. In this case the difference is a result of food shortage. We observe high mortality from starvation in Lapland nests: near 50% of second-hatched chicks die at ages from about 3 up to 5–6 wk (wing length 27–33 cm). This is not seen in nests on the coast or lakes in southern Sweden. Surviving chicks in Lapland eventually reach about the same weight as chicks on the coast from 7 wk of age. Age-specific body mass data from nestlings can also be used to monitor trends in condition and health within a population.

Since most raptors are sexually dimorphic, body mass records should ideally be assigned to either sex and treated separately. But sexing of raptor nestlings in the field can be difficult, and mixed samples may be useful as well in monitoring of trends, or to study differences between populations as exemplified in Figure 4. When sexing can be attained, a higher resolution in the studies can be achieved (35).

Detectable Changes

An important aspect in monitoring is the opportunity to detect changes and trends that are statistically significant. The chance of detecting a true trend, i.e., the statistical power, depends on several things, notably the magnitude of natural variation of the parameter(s) studied in the population, sample size, length of time series, etc. The sensitivity of a certain time series may be defined as the minimum trend possible to detect during a specified time period, e.g., 10 y, at a specified power, e.g., 80%.

The sample size for each year varies during the current monitoring period as the population increases over time. Larger sample sizes will give more reliable yearly estimates compared with small sample sizes. In order to quantify the effects of a reduced sampling program, artificial random sampling was carried out from the existing data base at successively smaller sample sizes. Table 4 shows that a reduction of the present monitoring program to a specified number of records (nest visits, number of broods) will decrease the sensitivity of the program. In Table 4, column G, some observed trends during a period of observed change are given for reference to the estimated detectable changes. If the maximum number of records is fixed to no more than 50 a year, the chance is still good to detect a reasonably small trend, at least in the Baltic Proper, whereas a reduction to only 10 or 25 is insufficient to detect trends that would be desirable to find. In the Gulf of Bothnia the between-year variance is larger, and a longer monitoring period than 10 y is required.

In addition to testing for linear trends, data from monitoring can be suitable for testing between different samples, e.g., between time periods or subpopulations. As an example, Figure 5 illustrates the development of sea eagle mean brood size on the Swedish Baltic coast from before year 1900 and into the 21st century. There is an obvious drop in mean brood size during the period, with an all-time low during 1966–1983. Contingency

Table 4. Minimum detectable yearly trend (%) for a 10-y monitoring period at a statistical power of 80%, based on data collected during 1991–2006: A) minimum detectable trend based on the raw data set between 1991–2006 (with a varying annual n of observations); B–F) minimum detectable trend at a maximum of 50, 25, 20, 15, and 10 n of visits, respectively. The estimates are based on the average of 5000 random samples from the database for each simulated n of visits; G) Observed average yearly trend 1986–1995 (%).

	A	B	C	D	E	F	G
Mean brood size (1–3)	n = 25–99	25–50	25	20	15	10	
Baltic Proper (%)	1.30	1.60	2.30	2.60	3.10	4.00	1.8
Mean brood size (1–3)	n = 14–51	14–50	14–25	14–20	14–15	10	
Gulf of Bothnia (%)	2.00	2.00	2.20	2.50	2.80	3.60	1.9
Success (0,1)	n = 45–161	45–50	25	20	15	10	
Baltic Proper (%)	3.60	4.20	5.50	6.00	6.90	8.50	8.0
Success (0,1)	n = 26–82	26–50	25	20	15	10	
Gulf of Bothnia (%)	2.20	2.40	3.90	4.70	5.80	7.70	1.5
Mean brood size (0–3)	n = 45–161	45–50	25	20	15	10	
Baltic Proper (%)	3.10	4.10	5.90	6.70	7.80	9.90	9.8
Mean brood size (0–3)	n = 26–82	26–50	25	20	15	10	
Gulf of Bothnia (%)	3.00	3.20	4.80	5.70	7.10	9.40	2.9

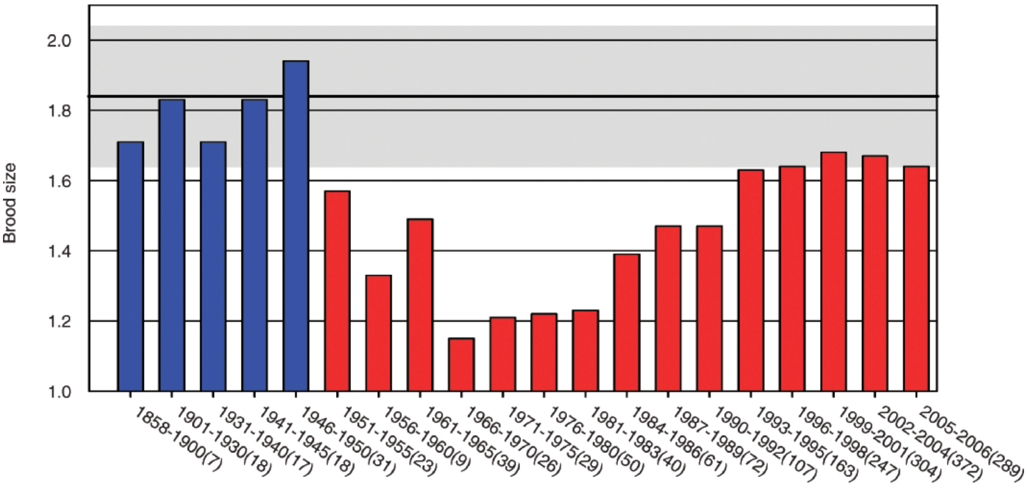

Figure 5. Mean brood size of white-tailed sea eagle on the Swedish Baltic coast over time. Sample size for each period is given in brackets. Reference level based on 1858–1950 is given with 95% confidence limits according to (7).

table analysis of the distribution of nests containing one and more than one nestling for the periods 1858–1950 *versus* 1951–1955 indicates that the proportion of nests containing more than one nestling decreased from 74% to 52%. This difference was almost significant ($p < 0.057$, $n = 114$), a slightly larger sample size of 120 would have been required, provided that the proportions would have remained the same.

Larger sample sizes, as available from the present monitoring program, allow for the detection of smaller differences: e.g., during 1996–2004, some 290 broods were recorded in the Gulf of Bothnia. A considerably lower proportion of nests containing more than one nestling was observed within a study area in county X, southern Bothnian Sea (see Fig. 1), compared with the rest of the gulf, only 42% compared to 59%. This difference was convincingly significant ($p < 0.015$). A sample size of only 190 had been sufficient at a significance level of 5%. At the 5% significance level, a sample size of 290 had been enough to show a difference 45% to 59%. This fairly small improvement in sensitivity (from 42% to 45%) in relation to increased effort (from 190 to 290) is due to the fact that the sensitivity to detect differences is not linearly related to the sample size—an increase to a small sample size will have a much larger effect than the same increase to a large sample size. Based on such calculations, sampling can be optimized to fit cost-benefit considerations.

The present monitoring program has shown differences between regions also in single years. For example in 2003, when 111 broods were recorded in the Gulf of Bothnia and the Baltic Proper altogether, the proportion of nests containing more than one nestling was significantly higher ($p < 0.007$) in the Baltic Proper (68%) compared with the Gulf of Bothnia (41%). A sample of 60 would have been sufficient to show this difference at a significance level of 5% and with unaltered sampling effort a proportion of nests with more than one nestling of 46% would still be significantly lower compared with the 68% in the Baltic Proper.

CONCLUDING REMARKS

The monitoring program of white-tailed sea eagle in Sweden has demonstrated a significant improvement in breeding success and brood size of the coastal population, from the lowest levels in the 1970s. Retrospective studies indicate that reproduction of this population began to deteriorate from ca. 1950 (36), (Fig. 5), but this was not really noted until 10 y later. The average annual decrease in the number of young per successful nest from the pre-1950 level to 1967 was about 2.5%, and the average annual decrease in breeding success over the same period was about 5% to 7%. Such trends would have been detectable with annual samples of 25 (Table 4). Thus, if monitoring of white-tailed eagle reproduction had been performed earlier during the 20th century, the negative impact from pollutants such as DDT could have been assessed already in the mid-1950s in the Baltic Sea. The significantly smaller brood size observed in the southern Bothnian Sea in recent years may be an indication of a regional pollution problem and has triggered investigations of other contaminants such as BFRs (33).

Being highly exposed to persistent chemicals, raptors are also useful in detecting the presence of "new" pollutants that are potentially harmful, as illustrated by the discovery of the polybrominated diphenylether (PBD) congener 209 in peregrine falcon eggs in Sweden (11). Sea eagles are particularly useful as biomonitors of aquatic environments to study the bioaccumulative effects of agricultural and industrial pollutants that end up in the water and increase in concentrations in consumers at all levels, but have the greatest potential for deleterious effects at the level of this ultimate top consumer (37). The importance of adequate sampling routines should be strongly emphasized in monitoring programs (38), and the power to detect changes under the programs should be investigated.

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