

Assessing Nesting Success and Productivity

KAREN STEENHOF

U.S. Geological Survey,
Forest and Rangeland Ecosystem Science Center,
Snake River Field Station, 970 Lusk Street, Boise, ID 83706 U.S.A.

IAN NEWTON

Centre for Ecology and Hydrology,
Monks Wood, Abbots Ripton, Huntingdon,
Cambridgeshire PE28 2LS, United Kingdom

INTRODUCTION

Studies of reproductive rates in raptors can be valuable in assessing the status of raptor populations and the factors that influence them. Estimates of nesting success and productivity provide insight into only one component of the demography of a raptor population. Individuals are added to local populations through reproduction, and they are subtracted through mortality. Together with immigration and emigration, these two demographic parameters determine the year-to-year trends in local populations. Reproductive rates usually are easier to evaluate than other aspects of demography, and properly designed studies will allow inferences to be made about relationships between the status of raptor populations and a variety of environmental influences. Unbiased data on reproductive rates allow comparisons among populations in different areas and different years that may reflect differences in land use, contaminant levels, human activity, or variations in natural phenomena, such as weather or prey supply. Such studies may

be essential for identifying effective conservation measures for threatened and declining species. Data on reproduction can help predict the effects of land use changes on raptor nesting populations (U.S. Department of Interior 1979), document effects of contaminants (Newton 1979, Grier 1982), or measure whether a population is reproducing well enough to sustain itself, given existing rates of survival (Henny and Wight 1972). Information on reproductive rates can be useful in deciding whether to list or reclassify an endangered raptor species or whether to allow harvest of a more common species for falconry purposes. Investigations have limited value, however, if objectives are not considered when the study is designed and initiated. Year-to-year fluctuations in nest success and productivity are common in raptors, and short-term decreases in productivity need not affect the long-term stability of populations.

The main objectives of this chapter are to (1) establish standard definitions that will facilitate comparisons of data over time and space, (2) identify the types of information needed to estimate raptor nesting success and productivity, (3) evaluate the advantages and disadvantages of various field techniques, and (4) offer suggestions for procedural and analytical approaches that will minimize bias. We include a glossary of technical terms for reference (Table 1).

CONCEPTS AND DEFINITIONS

To produce young, a raptor must pass successfully through a number of stages. It must first settle in a particular area, establish a **nesting territory** (terms in **bold**

are defined in Appendix 1), and acquire a mate. It must then proceed through **nest** building, egg laying, and then to hatching and rearing of young. In this sequential process, birds can fail at any stage.

For the purpose of analyzing reproductive data, a nesting territory is an area that contains, or historically contained, one or more nests (or **scrapes**) within the home range of a mated pair. The term nesting territory should not be confused with the more restricted ethological definition of a territory as any defended area. A raptor nesting territory can be thought of as a confined area where nests are found, usually in successive years, and where no more than one pair is known to have bred at one time (Newton and Marquiss 1982). The concept holds even in colonial species, in which the same nest sites tend to be used year after year with the occupants often defending only a small area around their nest.

Individuals that are unable to secure a nesting territory are known as **floaters**. They are usually unpaired and do not reproduce (Postupalsky 1983). Because of the difficulty in counting non-territorial raptors, and their greater mobility, they usually are excluded from analyses of **nesting success** and **productivity**. However, it may sometimes become possible to consider these birds in analyses of population dynamics (e.g., Kenward et al. 1999, Newton and Rothery 2001).

Some individuals are able to secure a nesting territory but not a mate. Postupalsky (1983) recommended that lone territorial birds be excluded from tallies of nesting pairs, but this is seldom practical. Territories that truly have only one adult are difficult to distinguish from those in which the second adult was absent at the time of the nest check, perhaps hunting some distance away. They also often represent only a temporary situation, as a lone bird may soon acquire a mate.

Certain pairs may occupy a territory for only a few days or a few weeks, or may even build a nest, but the process stops here. Not all raptor pairs occupying nesting territories lay eggs every year. A major factor influencing egg laying is food supply and in poor food years, many territorial pairs in some populations fail to lay eggs (Newton 2002). The proportion of pairs that produce eggs in different years, therefore, can be an important measure of a population's response to changing food supplies (Steenhof et al. 1997).

Still other territory holders may lay and then desert their eggs or lose them to predation, weather, or other causes. Others may produce eggs that hatch, but then their young die due to a variety of causes and at a variety of ages. Pairs that raise at least one young that is

nearly old enough to fly are usually considered **successful**. Of course, additional offspring mortality might occur after this stage (Marzluff and McFadzen 1996) when the young are free-flying, but still fed by their parents. Their death at this stage could be measured by a separate detailed study, or accounted for in estimates of juvenile survival, which is usually calculated as starting when the young are banded.

The proportions of pairs that reach these various stages can form a useful basis for comparing different raptor populations or subsets within populations. The most useful comparisons are based on the proportions of territorial pairs (or occupied territories) that produce young, but for practical reasons many studies can only obtain information on the proportion of laying pairs that produce young. Researchers who have good historical information on species that show strong fidelity to well-defined nesting territories (e.g., eagles, Ospreys [*Pandion haliaetus*]) can report nesting success and productivity on the basis of territorial pairs or occupied territories in a particular year (Brown 1974, Postupalsky 1974). In short-term investigations or studies of more nomadic raptors, it may be necessary to report success and productivity on the basis of laying pairs. For polygynous or polyandrous species (e.g., harriers, Harris's Hawks [*Parabuteo unicinctus*], etc.), success and productivity are best reported per mated territorial female or per mated male.

Estimates of productivity based solely on the number of young produced per successful pair can be misleading because successful pairs often produce average numbers of young even in years when most pairs fail (Steenhof et al. 1997, 1999). However, **brood size at fledging** can be a useful measure in some calculations (Steenhof and Kochert 1982: see below), depending on the purpose of the study.

CRITERIA FOR CLASSIFYING REPRODUCTIVE EFFORTS

Measurement error occurs when investigators incorrectly interpret the status of a particular pair or nesting territory, or incorrectly count the number of eggs or young. The ability to determine correctly the status of nests and to count the number of young varies with many factors, including the field situation, observer experience, and weather. Because these factors cannot be held constant, it is sometimes difficult to determine whether differences in estimates reflect measurement

error or true differences in productivity. Fraser et al. (1984) analyzed the problem of measurement error in aerial surveys of Bald Eagles (*Haliaeetus leucocephalus*) in the Chippewa National Forest. By running three simulated two-stage surveys in the same year, they were able to compute an error rate caused by mistakes in counts of occupied territories, laying pairs, and fledglings. Using this information, they calculated an estimated standard error that allowed them to test for true differences in productivity among years. The use of simulated surveys to obtain an estimate of variability due to measurement error is a site-specific procedure that must be repeated for each study area and each population. It is most valuable in situations where all territorial pairs have been found.

Territory Occupancy

Evidence that a territory is occupied can be based on observation of two birds that appear to be paired or one or more adults engaged in territorial defense, nest affinity, or other reproductive-related activity. Any indications that eggs were laid or young were reared constitute clear evidence for territorial occupancy. In some species, the presence of a nest that has been recently built, repaired, or decorated may constitute evidence for territorial occupancy, providing that these activities can be ascribed to the species of interest unequivocally. Caution must be used in applying this criterion because of the occasional difficulty in distinguishing old and new nest material. Fresh greenery, several sticks with fresh breaks, or a distinct layer of new material on top of older, weathered sticks usually suggest recent nest repair.

Individuals of some species may occupy territories for short periods only (perhaps less than one day), before moving on to another territory or reverting to a “floating” lifestyle. Some birds can thus easily be missed during a survey, or double-counted if they move from one territory to another in the same study area. Harriers are particularly problematic in this regard, because different individuals may “sky-dance” on different days over the same piece of nesting habitat during migration (e.g., Hamerstrom 1969). Fortunately, this seems not to be an issue for most species, and once a territory is occupied, it seems to remain so at least until the nest fails or the young reach independence.

For long-lived species that re-use the same territories year after year, such as Golden Eagles (*Aquila chrysaetos*) (Watson 1957) and Peregrine Falcons

(*Falco peregrinus*) (Mearns and Newton 1984), an estimate of the proportion of traditional territories occupied by pairs in any given year can be a useful index to the size and status of the nesting population. In species that show less fidelity to particular nesting territories among years, this measure can be misleading because it can grossly underestimate the status of species that normally use nesting territories intermittently or only once, such as Burrowing Owls (*Athene cunicularia*) (Rich 1984), Northern Hawk-Owls (*Surnia ulula*) (Sonerud 1997), Short-eared Owls (*Asio flammeus*) (Village 1987), and Ferruginous Hawks (*Buteo regalis*) (Lehman et al. 1998). For these and similar species, studies should be designed to sample all potential nesting habitat within a study area each year and not only previously occupied territories.

In many species, it is unusual to find all previously known territories occupied in any given year. Over a period of years, some territories may be used every year (or almost every year), whereas others are used irregularly, or very infrequently. In other words, certain territories are used much more often than expected by chance at the population levels found, and others are used much less often. This has led some long-term researchers to distinguish categories of territories, such as “regular and irregular.” Typically, occupants of “regular” territories are more often successful than are occupants of less used territories, giving a correlation between occupancy and nest success (Newton 1991, Sergio and Newton 2003). It seems that many raptors are capable of selecting those particular territories where their chances of raising young are high.

Egg Laying

Not all raptor pairs occupying nesting territories lay eggs every year (see above). Evidence of laying may be based on observations of eggs, young, an incubating adult, fresh eggshell fragments, or any other field sign that indicates eggs were laid. However, be aware that some species, such as the Bald Eagle, may assume incubation posture without actually having laid an egg (Fraser et al. 1983).

Laying Date

The laying date of the first egg usually is taken as a measure of the timing of breeding in birds. Laying date is useful because it often correlates with nest success; birds laying earliest in the season usually are the most

successful. Laying date also is a critical data element required for some **nest survival** models (Dinsmore et al. 2002). As nests are seldom visited on the very day that the first egg is laid, laying date is usually calculated indirectly, by backdating from some later stage in the cycle. Allowances are then made for the intervals between laying of successive eggs (two days in most raptor species), the **incubation period**, and, in the case of nests found during the **nestling period**, age of the young. Ages of nestlings can be estimated from weights or measurements in some species (e.g., Petersen and Thompson 1977, Bortolotti 1984). Photographic aging keys (e.g., Hoechlin 1976, Moritsch 1983a,b, 1985; Griggs and Steenhof 1993, Boal 1994, Priest 1997, Gossett and Makela 2005) also are useful tools for aging young. Repeated checks during the laying period can help to estimate the date of onset of incubation (Millsap et al. 2004). Otherwise, it is usually difficult to estimate laying date for pairs that fail during incubation. Investigators often assume that nest failure occurred at some specific stage, most typically in mid-incubation, or midway between successive nest checks, the latter check being the one in which failure was discovered. If deserted eggs are present, their stage of development sometimes can be estimated by candling (Weller 1956) to determine the stage of embryo growth, but the observer may still not know how long the eggs have lain unincubated in the nest.

Clutch Size

The number of eggs laid by each pair is useful, but not crucial, in assessments of overall productivity (Brown 1974). Because many raptor species nest on cliffs or in trees, not all nests are readily accessible, and clutch sizes may be difficult or impossible to record. In addition, some raptors are affected adversely by visits to nests during incubation. Because of this, counts of eggs at close range are sometimes associated with increased failure rates (Luttich et al. 1971, Steenhof and Kochert 1982, White and Thurow 1985, Chapter 19). For these reasons, a traditional measure of avian nesting success, the proportion of eggs that hatch and ultimately develop into fledglings, often is not attainable. Data on clutch sizes, however, can provide further insight into the mechanisms of a population's response to food supply or other environmental influences.

Nesting Success and Productivity

Nesting success is defined as the proportion of nesting or laying pairs that raise young to the age of **fledging** (i.e., the age when a fully-feathered offspring voluntarily leaves the nest for the first time). The difference between success per territorial pair and success per laying pair can be large in species that have relatively high rates of non-laying, including Golden Eagles and Tawny Owls (*Strix aluco*) (Southern 1970, Steenhof et al. 1997). It is less important for species in which all or most territorial pairs lay eggs (Steenhof and Kochert 1982).

In many studies, it is impossible to visit each nest on the exact day that young take their first flight; and after young have left the nest, they may be difficult to locate. Once young approach fledging age they become liable to flee from the nest prematurely if approached too closely. As they cannot fly at this stage, they usually flutter to the ground, and unless retrieved, could be vulnerable to predation or drowning. For this reason, it is sensible to check nests a week or more before young are likely to fledge. Most studies of raptors, therefore, consider pairs to be successful when well-grown young are observed in the nest at some point prior to fledging. Studies that consider nests with young of any age to be successful will overestimate nest success because they fail to consider mortality that may occur late in the brood-rearing period. Researchers should consider nest survival models (see below) when it is impossible to check an adequate number of nests at or near fledging.

If investigators wish to compare nest success among years, areas, or treatments, they should establish a standard minimum nestling age at which they consider nests to be successful. This age should be when young are well grown but not old enough to fly and at a stage when nests can be entered safely and after which mortality is minimal until actual fledging. Steenhof (1987) recommended that nests of diurnal raptors be considered successful only if at least one nestling has reached 80% of the average age at first flight. Mortality after this age until first flight is usually minimal (Millsap 1981). Furthermore, young are usually large enough to count from a distance at this stage. For Prairie Falcons (*F. mexicanus*), Golden Eagles, and Red-tailed Hawks (*B. jamaicensis*) nesting in the Snake River Canyon, 80% of fledging age corresponds with the age at which most young are banded (Steenhof and Kochert 1982). The 80% of first-flight age criterion has been used to determine nesting success in studies of several additional raptors, including Ferruginous Hawks, Northern Harriers (*Circus cyaneus*) (Lehman et al.

1998), Snail Kites (*Rostrhamus sociabilis*) (Bennetts et al. 1998), and Northern Goshawks (*Accipiter gentilis*) (Boal et al. 2005). A lower criterion for evaluating nest success (70 or 75% of the age at which young first leave the nest) might be more appropriate for species in which age at fledging varies considerably (i.e., highly sexually dimorphic raptors such as Cooper's Hawks [*A. cooperii*]) or for species that are more likely to leave the nest prematurely when checked. Millsap et al. (2004) considered Bald Eagle nests to be successful if young reached eight weeks of age or approximately 70% of first flight age, and the U.S. Fish and Wildlife Service (2003) considers Peregrine Falcon pairs to be successful when their young are at least 28 days old, or approximately 65% of first flight age. Information about fledging ages of most North American raptors can be found online at the Birds of North America website (<http://bna.birds.cornell.edu/BNA/>) (Poole 2004). Data on fledging ages of raptors from other parts of the world are in Newton (1979; Table 18) and Cramp et al. (1980). Investigators should consult more recent sources about their study species and use the best available information about variation in fledging ages and susceptibility to disturbance when they define and adopt a minimum age to evaluate success.

Productivity, which refers to the number of young that reach the minimum acceptable age for evaluating success, is usually reported on a per pair basis. In situations with a juvenile sex ratio of 1:1, the number of young per pair is equivalent to **fecundity** (number of females produced per female), a measure that can be incorporated into broader evaluations of a population's demography (e.g., Blakesley et al. 2001, Seamans et al. 2001). After leaving the nest, young normally continue to depend upon their parents (or one parent) for several weeks or months, before becoming independent and dispersing away from the nest vicinity. During the **post-fledging period**, young are sometimes difficult to locate (Fraser 1978). Counts after young have left the nest are unreliable because they tend to miss birds and underestimate the number of young produced. Owls present a special challenge in this regard because the young of many species leave the nest long before they can fly (Forsman et al. 1984) and often at staggered intervals (Newton 2002). Investigators should be aware that the number of young that leave the nest does not always correlate with the number of young that survive to disperse from the nesting territory (Marzluff and McFadzen 1996).

Nest failures. Evidence found at the nest may be

helpful in determining the proximate cause of a nest failure. Such signs might include intact, cold eggs, broken eggs, shell fragments, dead nestlings, nestling body parts, or hairs and feathers from likely nest predators. Unhatched eggs can be used for analyses of fertility or contaminant levels. Although a cause of failure often can be assigned in this way, it is important to remember that it may only be the proximate, and not the ultimate, cause. Thus, a female may be short of food, so desert her clutch, which might then be eaten by a predator, leaving shell fragments behind. In this case, the ultimate cause of failure was food shortage, but the proximate cause may be recorded as desertion or predation, depending on whether the observer happened to visit the nest before or after the predator. Nevertheless, assessing proximate causes of nest failure often has proved useful in defining conservation problems, including pesticide-induced shell thinning and egg-breakage (Ratcliffe 1980).

Repeat and double layings. In raptor species that have relatively short breeding cycles and long nesting seasons, pairs that fail early in the breeding cycle (during laying or early incubation) sometimes recycle, and lay another clutch. This usually occurs in a different nest within the same territory. The observer should be aware of this possibility, and check for repeat layings in likely circumstances. Repeat laying does not normally occur in pairs that fail at the nestling stage, presumably because by that stage in the season, pairs would not have time to raise the resulting young before the season ended. However, in at least 15 temperate zone species (Curtis et al. 2005), including Harris's Hawks (Bednarz 1995), American Kestrels (*F. sparverius*) (Steenhof and Peterson 1997), Barn Owls (*Tyto alba*) (Marti 1992), and Long-eared Owls (*A. otus*) (Marks and Perkins 1999), pairs sometimes produce more than one brood in a year. Snail Kites do not necessarily remain paired for successive nestings, but one partner remains to raise the young, while the other moves on, sometimes to re-pair and nest elsewhere (Beissinger and Snyder 1987). Each of these situations requires special attention and interpretation.

FIELD TECHNIQUES

Surveys for raptors may be conducted on foot or from ground vehicles, fixed-wing aircraft, helicopters, or boats (see Chapter 5). The value and accuracy of each of these techniques for locating breeding raptors and

their nests depends on the species being surveyed, the nesting substrate, observer experience, the topography and vegetation of the survey area, and the objective of the study. A combination of survey techniques may be most appropriate for specific situations.

Once found, nests on cliffs or trees can be checked from the ground in one of three ways: (1) remote observation, using telescopes or binoculars, (2) close inspection, accessing the nest using ropes or ladders, or (3) inspecting the nest from a short distance, perhaps using a mirror on a telescopic pole (Parker 1972). Mirrors mounted on 15-m poles proved useful in examining the contents of woodland raptor nests (Millsap 1981). Shorter mirror poles (up to 5 m) were used effectively to assess reproductive success of Ospreys nesting on navigational posts (Wiemeyer 1977). Binoculars or telescopes are ideal for cliff situations, but are not as useful where topography or dense vegetation prevents looking down into the nest from above. Observations from a distance may be adequate to confirm the presence of an incubating bird or of young, but they may be less useful in counting young, especially if the full contents of a nest are not visible.

Counts of nestlings from a distance can be particularly difficult if adults stay on the nest to brood or shade young. Climbing to nests is the best way to reduce error in counting young, but it also can be time-consuming and hazardous (see Chapter 10). Climbing requires special training, and the act of climbing to nests sometimes affects the birds adversely (Ellis 1973, Kochert et al. 2002, Chapter 19). Aerial surveys to assess reproduction are most appropriate for large raptors that build large nests in exposed locations. Aerial surveys of productivity have been effective for Ospreys (Carrier and Melquist 1976), Bald Eagles (Postupalsky 1974, Fraser et al. 1983), and Golden Eagles (Boeker 1970, Hickman 1972). In certain situations, helicopter surveys of Osprey reproductive success and productivity can be more cost-effective than ground surveys (Carrier and Melquist 1976), and fixed-wing aerial surveys of Osprey breeding pairs and numbers of fledged young can be as accurate as ground counts (Poole 1981). Both fixed-wing and helicopter surveys of nesting Golden Eagles may be more efficient and cost-effective than ground assessments (Boeker 1970, Hickman 1972, Kochert 1986).

It is easier to age and count young accurately from a slow-flying aircraft than from a fast, fixed-wing airplane (Hickman 1972, Carrier and Melquist 1976). For surveying Golden Eagle productivity, for example,

slow-flying aircraft, such as the Piper Super-Cub, which can travel at speeds of 70 to 120 kmph, are more economical than faster aircraft such as the Cessna 180 series (which travels 110 to 180 kmph) (Hickman 1972). Watson (1993) recommended quieter turbine-engine helicopters to minimize disturbance to Bald Eagles. Even with helicopters, investigators may not always be able to obtain complete brood counts, and ground-based surveys may be necessary to supplement aerial surveys. Most small fixed-wing or rotor-winged aircraft are acceptable for locating nesting pairs early in the season, but slow-flying Super-Cubs or helicopters are preferable during surveys conducted to count young. The accuracy of data can be increased if flights are scheduled for times when low winds improve maneuverability (Carrier and Melquist 1976). To minimize disturbance to Bald Eagles and to maximize safety and data reliability, Watson (1993) recommended conducting helicopter flights on calm, dry days, spending <10 seconds at each nest, staying at least 60 m from the nest, and using binoculars when necessary.

Artificial Nest Sites

Many raptor species breed in areas where a shortage of nesting sites limits nesting density. Provision of artificial sites (boxes or platforms, depending on species) can increase density, and also allow data on nesting success and productivity to be collected in an efficient manner. This is because the locations of all artificial sites are known, and they can be placed in accessible situations, so that nest contents can be easily inspected at every visit. Artificial nest sites, therefore, provide an extremely efficient means of data collection (for a study of more than 100 pairs of Common Kestrels (*F. tinnunculus*) nesting in boxes, see Cavé 1968). However, nesting success in artificial sites may not be the same as that in natural sites, which may be less secure or less sheltered, or vice versa.

Timing of Data Collection

Visits to raptor nests can yield useful information at any stage of the nesting cycle, but for adequate information on numbers and productivity, at least two visits are needed, one at the start of the nesting cycle (ideally around the time of egg-laying) and a second in the late nestling period (ideally just before young fledge). Because not all pairs start nesting at the same time, and, therefore, are out of phase with one another, the ideal

time for a survey is a compromise. When surveys of nesting raptors are conducted from aircraft, all pairs can be checked in a short period, but with ground-based surveys, nest checking may have to occur throughout much of the **breeding season**. The objective of the first series of checks is to count the number of pairs associated with nesting territories and (if conducted after laying) the number of pairs with eggs. Some researchers have made these checks after the last clutch has been laid, but before the first brood hatches (Fraser et al. 1983) and before many failures have occurred. In deciduous woodlands, initial surveys made before leaf-out allow nests to be seen more easily (Fuller and Mosher 1981).

The goal of the second set of observations is to count the number of successful pairs and the number of well-grown young. Timing is again a compromise — in this case, between the date that the last brood reaches the minimum acceptable age for success and the date that the earliest brood leaves the nest. In checks that involve close-range observation, care is needed so that frightened young do not leave the nest prematurely. Checks from aircraft or distant vantage points should be scheduled just prior to fledging so that young are large enough to be counted accurately.

Information on the nesting chronology of local raptor populations must be considered when scheduling all nest checks. Some species show wide variations in laying dates within populations, particularly in regions with warmer climates and extended breeding seasons. When there is considerable variation in nesting chronology, more than two surveys may be necessary (Postupalsky 1974). Similarly, when several species are being inventoried, more than two surveys may be needed to accommodate their separate chronologies. When nesting chronology is unknown or highly variable within a species, an intermediate survey after the young hatch, but before they leave the nest, may be necessary to age nestlings and determine when to schedule the final survey.

ANALYTICAL TECHNIQUES TO AVOID BIASED ESTIMATES

In many studies, estimates of nesting success and productivity are based on a sample of pairs rather than the entire nesting population in a defined area. **Sampling error** is the error that occurs when the pairs observed are not representative of the entire population. Obtaining a sample large enough to yield an unbiased estimate

of the parameters of interest is the researcher's greatest challenge. Because nests of most raptor species are relatively inaccessible and widely spaced, there has been a tendency to base productivity estimates on all pairs detected regardless of when or how they were found. The problem with this approach is that the probability of finding a pair is often related, directly or indirectly, to its position or reproductive status. For example, nests low in trees or near roads and openings may be easier to find (Titus and Mosher 1981), but their productivity may be affected by factors related to nest height (e.g., accessibility to predators) or proximity to roads (e.g., availability of road-killed prey).

A more serious problem, common to all studies designed to assess avian reproduction, is that non-laying or early-failing pairs are less likely to be detected than successful pairs (Newton 1979, p. 129). Non-layers spend less time near their nest sites than laying pairs, and unsuccessful pairs spend less time near their nests as the breeding season progresses (Fraser 1978). Non-nesters and unsuccessful pairs have larger home ranges (Marzluff et al. 1997), and unsuccessful pairs may even leave the area altogether soon after failure, especially in migratory populations. Nests with young are usually easier to locate because of audible vocalizations from the young and defending adults, or because of conspicuous "whitewash" or fecal matter around the nest. Because surveys that begin late in the nesting season tend to miss pairs that fail early, they may overestimate nesting success and productivity. Similarly, surveys that simply pool data from nests found at any stage throughout the nesting season also overestimate nest success (Mayfield 1961, 1975; Miller and Johnson 1978). In these situations, the ratio of the number of successful pairs to the total number of all pairs found is clearly of limited value and is equivalent to **apparent nest success** (Jehle et al. 2004).

One approach to minimize bias is to restrict analysis to pairs found prior to the nesting season, or if enough background data are available, to a set of pairs randomly selected prior to the nesting season (Steenhof and Kochert 1982). This approach requires that the success of all selected pairs be determined, but it is not necessary to distinguish non-laying pairs from unsuccessful laying pairs. It is practical only in situations where there is enough historical information on a species that tends to re-use traditional nesting territories (e.g., Golden Eagles). It is inappropriate for many other species of raptors and for most short-term investigations that lack previous information on territories. Some investigators

have tried to minimize bias by estimating nesting success only from laying pairs found early in the nesting season (Steenhof and Kochert 1982). However, this approach may greatly reduce sample size. When it is not possible to find all pairs before laying, researchers should consider using nest survival models to estimate the success of laying pairs.

Mayfield (1961) developed an approach to estimate nest success that incorporates data from nests found at various (and sometimes unknown) stages of the nesting cycle. By calculating **daily nest survival** during the time that a nest is under observation and by assuming a constant daily survival rate for all nests, Mayfield's model estimates the probability that all nests will survive over an entire **nesting period**. Several raptor studies have incorporated the Mayfield approach into their assessments of nesting success (e.g., Percival 1992, Bennetts and Kitchens 1997, Barber et al. 1998, Griffin et al. 1998, Lehman et al. 1998). Recently, more sophisticated models of nest survival have been developed that do not require Mayfield's assumption of constant daily survival throughout the nesting period (Dinsmore et al. 2002, Rotella et al. 2004, Shaffer 2004). Unlike Mayfield's original model, the newer models can include many categorical and continuous covariates that allow researchers to evaluate the importance of a variety of spatial and temporal factors that might affect nest survival. The new methods also allow competing models to be assessed via likelihood-based information-theoretic methods (Akaike 1973, Burnham and Anderson 2002). Nest survival models can be implemented in Program MARK (White and Burnham 1999) and in SAS (Rotella et al. 2004).

Nest-survival models allow data to be used from nests found at various times during the nesting season so long as the status of the nest was determined on at least two separate dates within the nesting period. If possible, nest checks should collectively span all stages of the nesting cycle. To use nest survival models, investigators need at least the following information: (1) the date the nest was found and its status on that date, (2) the last date the nest was checked and its status on that date, and, (3) the date the nest was last known to be viable if it had failed by the last check. Investigators also need to know the duration of the "nesting period" for their study species, which can be defined as the time from the laying of the first egg until the first young reaches the **minimum acceptable age for assessing success**. To calculate an appropriate nesting period for a given species, researchers should consider the length of

the laying and incubation periods in addition to the average age at first fledging. Information on each of these parameters is available in Newton (1979; Table 18), Cramp et al. (1980), and Poole (2004). The newer nest survival models have been used mainly for waterfowl, shorebirds, and passerines that nest on or near the ground (Dinsmore et al. 2002, Jehle et al. 2004, Rotella et al. 2004, Shaffer 2004). Raptor studies involving tree and cliff-nesting species differ from studies of ground-nesting birds in that many nests are observed remotely. Nest contents are not always inspected and there often is no way to estimate the age of nests that fail during incubation. In addition, many raptors have a longer nesting season, and many offspring continue to stay at or near the nest after they have made their first flight. Typically, investigators check raptor nests less often (sometimes only 2–3 times each season), and intervals between nest checks are usually longer than in studies of passerines, shorebirds, and waterfowl. For these reasons, adapting the new nest-survival models to raptors can be challenging, and nest survival models that require investigators to know the age of the nest when it is first found (e.g., Dinsmore et al. 2002) may not be useful for raptors. Moreover, studies with long intervals between nest checks may be limited in their ability to evaluate the effects of time-specific variables, including weather. Finally, nest survival models should only be used to estimate nesting success of laying pairs, because it is difficult to define when the nesting period begins for non-laying pairs.

Nest survival models currently available do not estimate survival of individual eggs or young. Therefore, estimates of productivity must be calculated differently. To estimate productivity, the estimate of nesting success must be combined with average brood size at fledging. To estimate productivity per territorial pair, this result must be combined with an independent estimate of the percentage of pairs laying eggs (Steenhof and Kochert 1982). Variances of productivity estimates obtained as products can be calculated using formulas available in Goodman (1960).

ACKNOWLEDGMENTS

This chapter is a contribution from the Snake River Field Station, Forest and Rangeland Ecosystem Science Center, Boise, Idaho and the Centre for Ecology and Hydrology, Huntingdon, United Kingdom. Discussions with Jon Bart, Mike Kochert, and Matthias Leu were

helpful in developing ideas presented in this chapter. We thank them and David E. Andersen, Robert E. Bennetts, Robert N. Rosenfield, William E. Stout, and S. Postupalsky for reviewing and commenting on an earlier draft of the manuscript.

LITERATURE CITED

- AKAIKE, H. 1973. Information theory and an extension of the maximum likelihood principle. Pages 267–281 in B. Theory, N. Petrov, and F. Csaki, [EDS.], Second International Symposium on Information. Akademiai Kiado, Budapest, Hungary.
- BARBER, J.D., E.P. WIGGERS AND R.B. RENKEN. 1998. Nest-site characterization and reproductive success of Mississippi Kites in the Mississippi River floodplains. *J. Wildl. Manage.* 62:1373–1378.
- BEDNARZ, J.C. 1995. Harris' Hawk (*Parabuteo unicinctus*). No. 146 in A. Poole and F. Gill [EDS.], The Birds of North America. The Birds of North America, Inc., Philadelphia, PA U.S.A.
- BEISSINGER, S.R. AND N.F.R. SNYDER. 1987. Mate desertion in the Snail Kite. *Anim. Behav.* 35:477–487.
- BENNETTS, R.E. AND W.M. KITCHENS. 1997. The demography and movements of Snail Kites in Florida. USGS/BRD Tech. Rep. No. 56, Florida Cooperative Fish and Wildlife Research Unit, University of Florida, Gainesville, FL U.S.A.
- , K. GOLDEN, V.J. DREITZ AND W.M. KITCHENS. 1998. The proportion of Snail Kites attempting to breed and the number of breeding attempts per year in Florida. *Fla. Field Nat.* 26:77–83.
- BLAKESLEY, J.A., B.R. NOON AND D.W.H. SHAW. 2001. Demography of the California Spotted Owl in northeastern California. *Condor* 103:667–677.
- BOAL, C.W. 1994. A photographic and behavioral guide to aging nestling Northern Goshawks. *Stud. Avian Biol.* 16:32–40.
- , D.E. ANDERSEN AND P.L. KENNEDY. 2005. Productivity and mortality of Northern Goshawks in Minnesota. *J. Raptor Res.* 39:222–228.
- BOEKER, E.L. 1970. Use of aircraft to determine Golden Eagle, *Aquila chrysaetos*, nesting activity. *Southwest. Nat.* 15:136–137.
- BORTOLOTTI, G.R. 1984. Criteria for determining age and sex of nestling Bald Eagles. *J. Field Ornithol.* 55:467–481.
- BROWN, L. 1974. Data required for effective study of raptor populations. Pages 9–20 in F.N. Hamerstrom, Jr., B.E. Harrell, and R.R. Olendorff [EDS.], Management of raptors. Raptor Research Report No. 2, Raptor Research Foundation, Inc., Vermillion, SD U.S.A.
- BURNHAM, K.P. AND D.R. ANDERSON. 2002. Model selection and multimodel inference: an information-theoretic approach, 2nd Ed. Springer-Verlag, New York, NY U.S.A.
- CARRIER, W.D. AND W.E. MELQUIST. 1976. The use of a rotor-winged aircraft in conducting nesting surveys of Ospreys in northern Idaho. *J. Raptor Res.* 10:77–83.
- CAVÉ, A.J. 1968. The breeding of the Kestrel, *Falco tinnunculus* L., in the reclaimed area Oostelijk Flevoland. *Neth. J. Zool.* 18:313–407.
- CRAMP, S., K.E.L. SIMMONS, R. GILLMOR, P.A.D. HOLLOW, R. HUDSON, E.M. NICHOLSON, M.A. OGILVIE, P.J.S. OLNEY, C.S. ROSELAAR, K.H. VOOUS, D.I.M. WALLACE AND J. WATTEL. 1980. Handbook of the birds of Europe, the Middle East and North Africa: the birds of the Western Palearctic. Oxford University Press, New York, NY U.S.A.
- CURTIS, O., G. MALAN, A. JENKINS AND N. MYBURGH. 2005. Multiple-brooding in birds of prey: South African Black Sparrowhawks (*Accipiter melanoleucus*) extend the boundaries. *Ibis* 147:11–16.
- DINSMORE, S.J., G.C. WHITE AND F.L. KNOPF. 2002. Advanced techniques for modeling avian nest survival. *Ecology* 83:3476–3488.
- ELLIS, D.H. 1973. Behavior of the Golden Eagle: an ontogenic study. Ph.D. dissertation, University of Montana, Missoula, MT U.S.A.
- FORSMAN, E.D., E.C. MESLOW AND H.M. WIGHT. 1984. Distribution and biology of the Spotted Owl in Oregon. *Wildl. Monogr.* 87:1–64.
- FRASER, J.D. 1978. Bald Eagle reproductive surveys: accuracy, precision, and timing. M.S. thesis, University of Minnesota, St. Paul, MN U.S.A.
- , L.D. FRENZEL, J.E. MATHISEN, F. MARTIN AND M.E. SHOUGH. 1983. Scheduling Bald Eagle reproduction surveys. *Wildl. Soc. Bull.* 11:13–16.
- , F. MARTIN, L.D. FRENZEL AND J.E. MATHISEN. 1984. Accounting for measurement errors in Bald Eagle reproduction surveys. *J. Wildl. Manage.* 48:595–598.
- FULLER, M.R. AND J.A. MOSHER. 1981. Methods of detecting and counting raptors: a review. *Stud. Avian Biol.* 6:235–246.
- GOODMAN, L.A. 1960. On the exact variance of products. *J. Am. Stat. Assoc.* 55:708–713.
- GOSSETT, D.N. AND P.D. MAKELA. 2005. Photographic guide for aging nestling Swainson's Hawks. BLM Idaho Tech. Bull 2005-01. Burley, ID U.S.A.
- GRIER, J.W. 1982. Ban of DDT and subsequent recovery of reproduction in Bald Eagles. *Science* 218:1232–1235.
- GRIFFIN, C.R., P.W.C. PATON AND T.S. BASKETT. 1998. Breeding ecology and behavior of the Hawaiian Hawk. *Condor* 100:654–662.
- GRIGGS, G.R. AND K. STEENHOF. 1993. Photographic guide for aging nestling American Kestrels. USDI Bureau of Land Management. Raptor Research Technical Assistance Center, Boise, ID U.S.A.
- HAMERSTROM, F. 1969. A harrier population study. Pages 367–383 in J.J. Hickey [ED.], Peregrine Falcon populations: their biology and decline. University of Wisconsin Press, Madison, WI U.S.A.
- HENNY, C.J. AND H.M. WIGHT. 1972. Population ecology and environmental pollution: Red-tailed and Cooper's hawks. Population ecology of migratory birds: a symposium. *USDI Wildl. Res. Rep.* 2:229–250.
- HICKMAN, G.L. 1972. Aerial determination of Golden Eagle nesting status. *J. Wildl. Manage.* 36:1289–1292.
- HOECHLIN, D.R. 1976. Development of golden eaglets in southern California. *West. Birds* 7:137–152.
- JEHLE, G., A.A. YACKEL ADAMS, J.A. SAVIDGE AND S.K. SKAGEN. 2004. Nest survival estimation: a review of alternatives to the Mayfield estimator. *Condor* 106:472–484.
- KENWARD, R.E., V. MARCSTRÖM AND M. KARLBOM. 1999. Demographic estimates from radio-tagging: models of age-specific survival and breeding in the Goshawk. *J. Anim. Ecol.* 68:1020–1033.

- KOCHERT, M.N. 1986. Raptors. Pages 313–349 in A.L. Cooperrider, R.J. Boyd, and H.R. Stuart [EDS.], Inventory and monitoring of wildlife habitat. Chapter 16. USDI Bureau of Land Management Service Center, Denver, CO U.S.A.
- , K. STEENHOF, C.L. MCINTYRE AND E.H. CRAIG. 2002. Golden Eagle (*Aquila chrysaetos*). No. 684 in A. Poole, and F. Gill [EDS.], The Birds of North America. The Birds of North America, Inc., Philadelphia, PA U.S.A.
- LEHMAN, R.N., L.B. CARPENTER, K. STEENHOF AND M.N. KOCHERT. 1998. Assessing relative abundance and reproductive success of shrubsteppe raptors. *J. Field Ornithol.* 69:244–256.
- LUTTICH, S.N., L.B. KEITH AND J.D. STEPHENSON. 1971. Population dynamics of the Red-tailed Hawk (*Buteo jamaicensis*) at Rochester, Alberta. *Auk* 88:75–87.
- MARKS, J. S. AND A.E.H. PERKINS. 1999. Double brooding in the Long-eared Owl. *Wilson Bull.* 111:273–276.
- MARTI, C.D. 1992. Barn Owl (*Tyto alba*). No. 1 in A. Poole, and F. Gill [EDS.], The Birds of North America. The Birds of North America, Inc., Philadelphia, PA U.S.A.
- MARZLUFF, J.M. AND M. MCFADZEN. 1996. Do standardized brood counts accurately measure productivity? *Wilson Bull.* 108:151–153.
- , B.A. KIMSEY, L.S. SCHUECK, M.E. MCFADZEN, M.S. VEKASY AND J.C. BEDNARZ. 1997. The influence of habitat, prey abundance, sex, and breeding success on the ranging behavior of Prairie Falcons. *Condor* 99:567–584.
- MAYFIELD, H.F. 1961. Nesting success calculated from exposure. *Wilson Bull.* 73:255–261.
- . 1975. Suggestions for calculating nest success. *Wilson Bull.* 87:456–466.
- MEARNS, R. AND I. NEWTON. 1984. Turnover and dispersal in a peregrine *Falco peregrinus* population. *Ibis* 126:347–355.
- MILLER, H.W. AND D.H. JOHNSON. 1978. Interpreting the results of nesting studies. *J. Wildl. Manage.* 42:471–476.
- MILLSAP, B.A. 1981. Distributional status of falconiformes in west central Arizona - with notes on ecology, reproductive success and management. Technical Note 355. USDI Bureau of Land Management, Phoenix District Office, Phoenix, AZ U.S.A.
- , T. BREEN, E. MCCONNELL, T. STEFFER, L. PHILLIPS, N. DOUGLASS AND S. TAYLOR. 2004. Comparative fecundity and survival of Bald Eagles fledged from suburban and rural natal areas in Florida. *J. Wildl. Manage.* 68:1018–1031.
- MORITSCH, M.Q. 1983a. Photographic guide for aging nestling Prairie Falcons. USDI Bureau of Land Management, Boise, ID U.S.A.
- . 1983b. Photographic guide for aging nestling Red-tailed Hawks. USDI Bureau of Land Management, Boise, ID U.S.A.
- . 1985. Photographic guide for aging nestling Ferruginous Hawks. USDI Bureau of Land Management, Boise, ID U.S.A.
- NEWTON, I. 1979. Population ecology of raptors. Buteo Books, Vermillion, SD U.S.A.
- . 1991. Habitat variation and population regulation in Sparrowhawks. *Ibis* 133 suppl. 1:76–88.
- . 2002. Population limitation in Holarctic owls. Pages 3–29 in I. Newton, R. Kavanagh, J. Olsen, and I. Taylor [EDS.], Ecology and conservation of owls. CSIRO Publishing, Collingwood, Victoria, Australia.
- AND M. MARQUISS. 1982. Fidelity to breeding area and mate in Sparrowhawks *Accipiter nisus*. *J. Anim. Ecol.* 51:327–341.
- AND P. ROTHERY. 2001. Estimation and limitation of numbers of floaters in a Eurasian Sparrowhawk population. *Ibis* 143:442–449.
- PARKER, J.W. 1972. A mirror and pole device for examining high nests. *Bird-Banding* 43:216–218.
- PERCIVAL, S. 1992. Methods of studying the long-term dynamics of owl populations in Britain. Pages 39–48 in C.A. Galbraith, I.R. Taylor, and S. Percival [EDS.], The ecology and conservation of European owls; proceedings of a symposium held at Edinburgh University. UK Nature Conservation; No. 5. Joint Nature Conservation Committee, Peterborough, United Kingdom.
- PETERSEN, L.R. AND D.R. THOMPSON. 1977. Aging nestling raptors by 4th-primary measurements. *J. Wildl. Manage.* 41:587–590.
- POOLE, A. 1981. The effects of human disturbance on Osprey reproductive success. *Colonial Waterbirds* 4:20–27.
- [ED.]. 2004. The Birds of North America Online. Retrieved January 15, 2005 from The Birds of North American Online database: <http://bna.birds.cornell.edu/> Cornell Laboratory of Ornithology, Ithaca, NY U.S.A.
- POSTUPALSKY, S. 1974. Raptor reproductive success: some problems with methods, criteria, and terminology. Pages. 21–31 in F.N. Hamerstrom Jr., B.E. Harrell, and R.R. Olenoff [EDS.], Raptor Research Report No. 2. Management of raptors. Raptor Research Foundation, Inc., Vermillion, SD U.S.A.
- . 1983. Techniques and terminology for surveys of nesting Bald Eagles. Appendix D in J.W. Grier et al. [EDS.], Northern states Bald Eagle recovery plan. USDI, Fish and Wildlife Service, Twin Cities, MN U.S.A.
- PRIEST, J.E. 1997. Age identification of nestling Burrowing Owls. Pages 127–127 in J.L. Lincer, and K. Steenhof [EDS.], The Burrowing Owl, its biology and management including the proceedings of the first international burrowing owl symposium. Raptor Research Report No. 9, Raptor Research Foundation, Allen Press, Lawrence, KS U.S.A.
- RATCLIFFE, D.A. 1980. The Peregrine Falcon. Buteo Books, Vermillion, SD U.S.A.
- RICH, T. 1984. Monitoring Burrowing Owl populations: implications of burrow re-use. *Wildl. Soc. Bull.* 12:178–180.
- ROTELLA, J.J., S.J. DINSMORE AND T.L. SHAFFER. 2004. Modeling nest-survival data: a comparison of recently developed methods that can be implemented in MARK and SAS. *Anim. Biodiversity Conserv.* 27:1–19.
- SEAMANS, M.E., R.J. GUTIÉRREZ, C.A. MOEN AND M.Z. PEERY. 2001. Spotted Owl demography in the central Sierra Nevada. *J. Wildl. Manage.* 65:425–431.
- SERGIO, F. AND I. NEWTON. 2003. Occupancy as a measure of territory quality. *J. Anim. Ecol.* 72:857–865.
- SHAFFER, T.L. 2004. A unified approach to analyzing nest success. *Auk* 121:526–540.
- SONERUD, G. 1997. Hawk Owls in Fennoscandia: population fluctuations, effects of modern forestry, and recommendations on improving foraging habitats. *J. Raptor Res.* 31:167–174.
- SOUTHERN, H.N. 1970. The natural control of a population of Tawny Owls (*Strix aluco*). *J. Zool. Lond.* 162:197–285.
- STEENHOF, K. 1987. Assessing raptor reproductive success and productivity. Pages 157–170 in B.A. Giron Pendleton, B.A. Millsap, K.W. Cline, and D.M. Bird [EDS.], Raptor management techniques manual. National Wildlife Federation, Washington, DC U.S.A.
- AND M.N. KOCHERT. 1982. An evaluation of methods used to estimate raptor nesting success. *J. Wildl. Manage.* 46:885–893.

- AND B. PETERSON. 1997. Double brooding by American Kestrels in Idaho. *J. Raptor Res.* 31:274–276.
- , M. N. KOCHERT, L.B. CARPENTER AND R.N. LEHMAN. 1999. Long-term Prairie Falcon population changes in relation to prey abundance, weather, land uses, and habitat conditions. *Condor* 101:28–41.
- , M.N. KOCHERT AND T.L. McDONALD. 1997. Interactive effects of prey and weather on Golden Eagle reproduction. *J. Anim. Ecol.* 66:350–362.
- TITUS, K. AND J.A. MOSHER. 1981. Nest-site habitat selected by woodland hawks in the central Appalachians. *Auk* 98:270–281.
- U.S. DEPARTMENT OF THE INTERIOR. 1979. Snake River Birds of Prey Special Research Report to the Secretary of the Interior. USDI Bureau of Land Management, Boise District, Boise, ID U.S.A.
- U.S. FISH AND WILDLIFE SERVICE. 2003. Monitoring plan for the American Peregrine Falcon, a species recovered under the Endangered Species Act. U.S. Fish and Wildlife Service, Divisions of Endangered Species and Migratory Birds and State Programs, Pacific Region, Portland, OR U.S.A.
- VILLAGE, A. 1987. Numbers, territory size and turnover of Short-eared Owls *Asio flammeus* in relation to vole abundance. *Ornis Scand.* 18:198–204.
- WATSON, A. 1957. The breeding success of Golden Eagles in the northeast highlands. *Scott. Nat.* 69:153–169.
- WATSON, J.W. 1993. Responses of nesting Bald Eagles to helicopter surveys. *Wildl. Soc. Bull.* 21:171–178.
- WELLER, M.W. 1956. A simple field candler for wildfowl eggs. *J. Wildl. Manage.* 20:111–113.
- WHITE, C.M. AND T.L. THUROW. 1985. Reproduction of Ferruginous Hawks exposed to controlled disturbance. *Condor* 87:14–22.
- WHITE, G.C. AND K.P. BURNHAM. 1999. Program MARK - estimation from populations of marked animals. *Bird Study* 46 Supplement:120–138.
- WIEMEYER, S.N. 1977. Reproductive success of Potomac River Ospreys, 1971. Pages 115–119 in J.C. Ogden [Ed.], Transactions of the North American Osprey Research Conference. Transactions and Proceedings Series No. 2. USDI National Park Service, Washington DC U.S.A.

Appendix 1. Glossary of terms frequently used in assessing nesting success.*

Active. An ambiguous term, originally defined by Postupalsky (1974) to describe nests where pairs laid eggs, but used subsequently in many different ways by other authors. The term is now best avoided (S. Postupalsky, pers. comm.), unless clearly defined.

Apparent Nest Success. The ratio of number of successful pairs to the total number of known pairs in a population.

Breeding Season. The period from the start of nest building (refurbishment) or courtship to independence of young.

Brood Size at Fledging. The number of young produced by successful pairs.

Clutch Size. The number of eggs laid in a nest.

Daily Nest Survival. The probability that at least one young or egg in a nest will survive a single day.

Fecundity. The number of female young produced per female. Equivalent to number of young produced per pair, assuming a 1:1 sex ratio among offspring.

Fledging. A fully-feathered young voluntarily leaving the nest for the first time.

Floaters. Birds in either subadult or adult plumage that are not associated with specific nesting territories and do not reproduce. Floaters may be physiologically capable of breeding, but are prevented from doing so by lack of a territory or nesting site. They are usually unpaired.

Incubation Period. The time between the start of incubation and the hatching of an egg, during which the egg is kept at or near body temperature by the parent.

Irregular Territory. Known nesting location occupied only in certain years out of many.

Measurement Error. Misclassification of the status of a particular pair or nesting territory or an inaccurate count of the number of eggs or young.

Minimum Acceptable Age for Assessing Success. A standard nestling age at which a nest can be considered successful. An age when young are well grown but not old enough to fly and at a stage when nests can be entered safely and after which mortality is minimal until actual fledging: 80% of the age that young of a species normally leave the nest of their own volition for many species, but lower (65–75%) for species in which age at fledging varies considerably or for species that are more likely to leave the nest prematurely when checked. Often the same as age at banding.

Nest. The structure made or the place used by birds for laying their eggs and sheltering their young.

Nesting Period. The time from laying of the first egg to the time when at least one young reaches the minimum acceptable age for evaluating success in a given species. This interval can be used to calculate nesting success from estimates of daily survival rates. It can be calculated as the sum of the minimum acceptable age for assessing success, the mean incubation period, and the mean time between laying of the first egg and the onset of incubation.

Nestling Period. The time between hatching of the first egg and the time the first young leaves the nest of its own accord.

Nesting Success. The proportion of pairs that raise at least one young to the minimum acceptable age for assessing success (see above) in a given season, even if it takes >1 attempt. Usually reported per territorial pair or per laying pair.

Nesting Territory. An area that contains, or historically contained, one or more nests (or scrapes) within the home range of a mated pair: a confined locality where nests are found, usually in successive years, and where no more than one pair is known to have bred at one time.

Nest Survival. The probability that a nesting attempt survives from initiation (laying of the first egg) to completion and has at least one offspring that reaches the minimum acceptable age for assessing success.

Nonbreeders. A collective term to describe both floaters and territorial pairs that do not produce eggs.

Post-fledging Period. The time between when young leave the nest (i.e., fledge) and their becoming independent of parental care. Sometimes measured from the time young are banded or are old enough for nests to be considered successful.

Pre-incubation Period. The time between laying of the first egg and onset of incubation.

Productivity. The number of young that reach the minimum acceptable age for assessing success; usually reported as the number of young produced per territorial pair or per occupied territory in a particular year.

Regular Territory. Known nesting territory, in use every, or almost every, year.

Sampling Error. Error that occurs when the pairs observed are not representative of the entire population.

Scrape. A site where falcons, owls, and New World vultures (species that do not construct nests) lay eggs; the depression in substrate (rotting wood chips, old pellets, dust, sand, or gravel) where eggs are deposited.

Successful (nest or pair). One in which at least one young reaches minimum acceptable age for assessing success.

* Although definitions in this Glossary are widely accepted among raptor researchers, not everyone uses particular terms in exactly the same way. Therefore, care is needed in making comparisons among studies. It is important to avoid using a familiar term in a different context, and it is equally important to define your terms carefully in your methods section. Doing so will make it easier for others to assess your findings, and to compare them with those of other researchers.

B. Satellite Tracking

BERND-U. MEYBURG

World Working Group on Birds of Prey,
Wangenheimstrasse 32, D-14193 Berlin, Germany

MARK R. FULLER

U.S. Geological Survey, Forest Rangeland Ecosystem
Science Center, Snake River Field Station, and
Boise State University Raptor Research Center,
970 Lusk Street, Boise, ID 83706 U.S.A.

INTRODUCTION

Satellite telemetry has revolutionized the study of raptor migration and life histories and will continue to do so in the future (Table 1). This is because tracking systems used in satellite telemetry can regularly estimate and record an individual's location worldwide for several years. Satellite telemetry with birds started in the 1980s (Strikwerda et al. 1986). Since then, satellite telemetry has been based on Ultra High Frequency (UHF) technologies such as the Argos system, that includes the Collecte Localisation Satellites (CLS). More recently, transmitters and Global Positioning Systems (GPS) receivers have become small enough to use on birds. In some cases GPS satellite telemetry will soon supersede land-based VHF tracking.

The Argos System

Satellite telemetry for raptor studies has used the Argos

system. Individual birds must be able to carry transmitters, called Platform Transmitter Terminals (PTTs), weighing about 5 g or more. The Argos system provides location estimates and sensor data (e.g., battery voltage, activity, temperature, pressure) from PTTs anywhere around the world. The basics of operation are described in the Argos User Manual (www.argosinc.com/system_overview.htm). Additional recent information is available in the *Proceedings of the Argos Animal Tracking Symposium, 24–26 March 2003* (CLS America 2003), which is available on CD from CLS America, 1441 McCormick Drive, Suite 1050, Largo MD 20774.

Location Estimates of Transmitters by Argos

PTTs are located using the Doppler phenomenon. Polar-orbiting satellites carry Argos receivers. As a satellite approaches the PTT, the frequency received will be higher than the nominal transmitted frequency (401.650 MHz), whereas frequencies lower than 401.650 MHz will be received at the satellite as it moves away from the PTT. At the point of inflection of the Doppler curve, that is, when the received and transmitted frequencies are equal, the position of the transmitter will be perpendicular to the satellite ground track. The system estimates two possible PTT locations, which are symmetrical on each side of the satellite ground track. Argos selects one of these as plausible, but biologists should confirm the validity of the location selected by Argos.

Location estimates based on PTT transmissions and the Argos satellite system are assigned to location classes (LC). "Location accuracy varies with the geometri-

Table 1. Topics and questions regarding raptors for which data from satellite telemetry have or are expected to provide information. Some references are provided, and more can be found at the U.S. Geological Survey Raptor Information System (<http://ris.wr.usgs.gov/>). The keywords below and others can be used to find citations to publications listed in the Raptor Information System.

Annual Movements	<ul style="list-style-type: none"> • Annual movements (Brodeur et al. 1996, Fuller et al. 2003, Meyburg et al. 2004b, Laing et al. 2005, Steenhof et al. 2005) • Differences among years (Alerstam et al. 2006)
Migration	<ul style="list-style-type: none"> • Mapping routes of migrating raptors (Meyburg et al. 1995a, 1995b; Brodeur et al. 1996, Fuller et al. 1998, Ellis et al. 2001) • Individual variation (Alerstam et al. 2006) • Ecological barriers, leading lines (sea, mountains, deserts) (Meyburg et al. 2002, 2003) • Bottlenecks; do all individuals pass a narrow area, at what time? (Fuller et al. 1998) • Navigation and orientation (Hake et al. 2001, Thorup et al. 2003a, 2003b, 2006b) • Migration period and timing (Schmutz et al. 1996, Kjellen et al. 2001, Meyburg et al. 2004b) • Age and sex differences, breeding status (Ueta et al. 2000, Ueta and Higuchi 2002, Hake et al. 2003, McGrady et al. 2003, Meyburg et al. 2005, 2006, Soutullo et al. 2006b) • Speed and altitude of migration (Hedenström 1997, Kjellen et al. 2001) • Variation throughout migration (Meyburg et al. 2006) • Daily distances, travel rates (Fuller et al. 1998, Meyburg et al. 1998, Soutullo et al. 2006a) • Daily behavior, stopovers (time of starting and stopping), hunting (Meyburg et al. 1998) • Weather conditions (Meyburg et al. 1998, Thorup et al. 2003b, 2006a) • Ecological conditions along migration routes
Winter or Austral Summer	<ul style="list-style-type: none"> • Geographical situations of wintering grounds (Woodbridge et al. 1995, Martell et al. 2001, Haines et al. 2003, Higuchi et al. 2005, Steenhof et al. 2005) • Discovery of unknown wintering grounds (Meyburg et al. 1998) • Ranges on wintering grounds (McGrady et al. 2002) • Fidelity to the same area in successive years (Fuller et al. 2003)
Nesting Season	<ul style="list-style-type: none"> • Home range size, habitat use, and territorial behavior (Meyburg et al. 2006) • Dispersal, philopatry (Rafanomezantsoa et al. 2002, Steenhof et al. 2005) • What accounts for later or earlier arrival in spring at the nest site (influence of weather during migration, later or earlier departure to wintering grounds) (Meyburg et al. 2007b) • Pair continuity over a number of years (Meyburg 2007a) • Behavior of nonbreeding adults, floaters (arrival, fidelity to nest site after failed nesting attempt, possible nomadism) (Meyburg 2007b)
Movements during Immature Stage	<ul style="list-style-type: none"> • Return to breeding area or remain on the “wintering grounds” (Meyburg et al. 2004a) • Ranging behavior (Meyburg et al. 2004a)
Survival, Mortality, Threats	<ul style="list-style-type: none"> • Human activity (Eastham et al. 2000) • Other causes (Goldstein et al. 1999, Hooper et al. 1999, Henny et al. 2000, Millsap et al. 2004, Steenhof et al. 2006) • Fate of release birds (Rose et al. 1993, Launay and Muller 2003, Dooley et al. 2004)

cal conditions of the satellite passes, the stability of the transmitter oscillator, the number of messages collected and their distribution in the pass. This means in particular that a given transmitter can have locations distributed over several classes during its lifetime. Classes for which accuracy is estimated and their related values: Class 3: better than 150 m on both axes, 250 m radius, Class 2: better than 350 m, 500 m radius, Class 1: better than 1000 m, 1500 m radius, Class 0: over 1000 m, 1500 m radius. These are estimations at one sigma.” (www.cls.fr/html/argos/general/faq_en.html).

Argos location methods are based on three major assumptions: (1) transmission frequency is stable during the satellite pass, (2) the PTT is motionless during the satellite pass, and (3) the altitude of the PTT is known. The LC assigned by Argos usually underestimates the error associated with wildlife applications largely because these assumptions often are violated to some extent when the PTT is on an animal (e.g., Britten et al. 1999, Craighead and Smith 2003). Usually, the accuracy given by Argos is better for the latitude than for the longitude. The given accuracy (e.g., 1 km for LC 1) does not mean that all of the calculated locations (and attributed to LC 1) fall within 1 km, but that about one sigma (one standard deviation) of all estimates are in the nominal accuracy range.

It is important to remember that the best two LCs (LC 2 and LC 3) usually are achieved only 10% to 15% of the time from birds. This occurs for numerous reasons, not the least of which is that many wildlife PTTs do not transmit 1 W of power, upon which the Argos system was designed. Power often is programmed to 0.15 to 0.25 W to conserve energy for prolonged PTT operation. Power output in solar-powered PTTs is adjustable (e.g., from 0.1 to 0.5 W). Reduced radiated power can result in fewer location estimates, and consequently fewer data with which Argos can estimate locations most accurately.

Argos routinely provides Standard LCs (LC 3, LC 2, LC 1, see above), but also can provide Auxiliary LCs (LC 0 > 1000 m, LC A and LC B = no estimate of location accuracy, and LC Z = invalid locations). The Auxiliary LCs are especially important because often there are few Standard LCs from wildlife tracking. Furthermore, the best LC classes do not always include the most accurate location estimates. Thus, wildlife researchers, especially those tracking birds, will want as many location estimates as possible from which to select appropriate data.

Location-estimate error from a given project can

vary dramatically depending on the speed of the animal and its behavior, including changes in elevation or altitude (www.cls.fr/manual/; see Appendix 2, Argos location), environmental variables (topography, vegetative cover, marine, atmospheric conditions), and data acquisition and analysis options. Users may specify to Argos values for some factors (e.g., PTT velocity, altitude) and discuss options (e.g., use of digital elevation model, multi-satellite service), and Argos will incorporate these in the estimation procedures. Users also should consult with equipment manufacturers to maximize performance (e.g., PTT power, transmission repetition rate) for the circumstances and objectives of the study. Biologists must determine if the Argos system is appropriate for their objectives, especially if they require regular location accuracy of less than 1 km.

Reduced Argos Performance

A significant difference in actual receptions of PTT transmissions exists in the European region and in Asia (Mongolia, China, Japan), and thus can reduce receptions to less than 10% of the expected data. The affected area is about the size of the satellite footprint (5,000 km in diameter) and seems to be centered in the region of southern Italy (Howey 2005). The cause is ambient broadband noise of significant amplitude around the Argos operating frequencies, which causes interference and affects all PTTs, including GPS models. It essentially limits the number of signals that are received by the satellite (Gros and Malardé 2006). We recommend that users contact CLS to discuss their specific requirements and take advantage of ways to optimize Argos system performance.

Argos Data-validation Procedures

Researchers should examine and carefully filter location estimates before selecting those for analyses. Filtering or data validation procedures usually involve establishing criteria based on animal movement capabilities and behavior (e.g., maximum speed, local versus migration movement; Hays et al. 2001) and inspecting the Argos data for time and distance relationships among location estimates. Many LC 0, LC A, and LC B class points might need to be discarded by filtering, but so might some LC 1, LC 2, and even LC 3 class points. Careful screening also might reveal that some LC 0, LC A, and LC B locations are well within the distance that an animal could have traveled during the period

between location estimates, and within a direction that is logical.

Raptor researchers must remember that locations from Argos are estimates and that accuracy and precision vary with animal and environmental factors that are largely unknown. In our experience, the proportion of higher quality LCs (LC 2 and LC 3) varies among PTT-marked animals. Therefore, we recommend that each person establish criteria for the study objectives, species, and environment and then apply those criteria when selecting the location estimates to be used in analyses.

Data Transmission through the Argos System

PTTs transmit a coded identification and data from up to 32 sensors. The signals are digitally encoded on a pulse width of ~ 0.36 seconds and a pulse interval usually between 40 and 90 seconds. The transmitting schedule (i.e., the duty cycle) can be programmed for more transmissions during different periods (e.g., seasons), which can prolong the operational life of battery-powered PTTs.

Transmissions from PTTs are received on polar orbiting satellites and are relayed to processing centers in France and the United States. Records of processed data can be distributed to users in a variety of formats, including Internet access to data received about four hours previously. The cost of data acquisition from Argos varies according to the different agreements between countries and Argos. Costs are assessed as a fee for use of each active platform, for hours of use per day, automatic data distribution service (data via email), fax, telnet, data acquired from the Argos website, and monthly compact discs (CD).

GPS Location of Transmitters

The GPS provides location accuracy to within a few meters. A GPS receiver can be integrated with an Argos PTT. A GPS receiver collects transmissions from at least four satellites, enabling computing of position (in three dimensions), velocity, and time. GPS units can be programmed to collect data at pre-set intervals. Data can be logged in memory and downloaded from the unit (usually requiring recapture), or they can be coded in PTT messages and relayed to users via the Argos system. The GPS estimates are transmitted to Argos during the "on time" of a PTT duty cycle.

The GPS receiver requires considerable energy. Thus, there are radio-tag size and longevity constraints that come into play when using battery power for bird studies. Alternatively, solar-powered GPS-PTTs weigh as little as 22 g. These units include sensors and a 12-channel GPS receiver.

Selection of the PTT

A crucial consideration when choosing a unit is how the PTT size, weight, and attachment might affect the bird (Murray and Fuller 2000). The energy requirements for satellite telemetry limit the minimum mass of units to about 5 g. The mass of the transmitter increases the energy the bird must expend for locomotion. Battery mass and surface areas of solar arrays also are limiting factors for unit size.

Deciding whether to use battery- or solar-powered tags must be made early in study planning. Battery-powered PTTs offer generally reliable performance, but have the disadvantage of a rather short operating life, thus long-term studies (more than three years) normally are not possible. Using 30- to 90-g battery-powered PTTs we regularly received locations from 6 to 18 months, depending on radiated power and duty cycle. Solar-powered transmitters can provide locations for up to several years, and the regularity of data is dependent on enough light on the solar array to charge a battery or capacitor with energy for transmission of the radio signal. Solar-powered GPS-PTT tags need more energy than PTTs. Thus, the problem of recharging these tags is even more acute. One must be sure the feathers do not occlude the solar array to the extent that there is insufficient exposure to light for minimal PTT function. Bird habitat use, such as under-canopy or cave nesting, also can affect solar charging.

The decision of whether to use solar or battery-powered PTTs depends not only on the geography and expected movements of the species to be studied, but also on other factors such as budget, lifestyle of the species, aim of the study (long- versus short-term), etc. In 2007 the price of a PTT was about \$3000 (U.S.), and that of a GPS-PTT was about \$4000. Costs of delivering data (see above) for several years can be as much or even more than the tag price, depending on how tags are programmed and what Argos services are used.

Attachment of Transmitters

Radio tags can be mounted on tail-feathers, legs, and

wings, but in most studies they are attached to the bird's back using a harness (Fuller et al. 2005). These "backpacks" have the advantage of being fixed near the center of lift which is best for high tag mass. Tags can be fitted to nestlings just before fledging and can be tracked for several years. Most researchers use Teflon[®] ribbon as harness material, but we found that some raptors (e.g. Asian Imperial Eagles [*Aquila heliaca*] and Lesser Spotted Eagles [*A. pomarina*], Prairie Falcons [*Falco mexicanus*]) remove tags by pulling and cutting through the Teflon[®] strips with their beaks (Steenhof et al. 2006). The potential complication of feathers over the solar panels on backpacks might be overcome by incorporating a feather guard (Snyder et al. 1989) or thick neoprene rubber on the bottom of the transmitter to elevate the solar array. These modifications might create additional aerodynamic drag and thus, energy needed for flight.

What Causes Termination of Transmissions?

Manufacturers can program a unit to stop transmitting, but most researchers probably would like to receive transmissions for as long as possible. Battery-powered units transmit information about battery voltage so that one can predict depletion of the battery energy. Often however, failure to receive transmissions occurs earlier than expected, raising a question as to what has happened. The causes of failure to receive data are sometimes difficult to determine.

Juvenile and immature birds often die from "natural causes," or perish from persecution. Adults also are subject to heavy persecution in many parts of the world or are killed by electrocution, collisions, etc. Nevertheless, based on observing the bird, recapturing it, or finding it dead much later, we confirmed that several solar-powered PTTs had failed while the birds were alive. In some cases we, or the manufacturer, were unable to determine a reason for the failure. Study planning should account for death of radio-marked birds and the failure of some transmitters.

Our record for long-term tracking is an adult female Greater Spotted Eagle (*A. clanga*). The bird was fitted with a PTT in July 1999 that was still transmitting data in August of 2007. An adult male Lesser Spotted Eagle was tracked as far as Israel on its way back to the breeding grounds almost 6 years after having been marked. When it arrived one month later in Germany we observed the bird with its PTT without an antenna. An

Osprey also lost or removed the antenna after only a few months. It is much easier to find the reasons for tag failure in breeding adults that return to their nest site year after year. There are methods for locating PTTs that are transmitting from a dead bird or detached from the bird (Howey 2002, Bates et al. 2003, Peske and McGrady 2005). Finding the PTT can provide valuable biological information and be cost-effective because most units can be refurbished for about \$300 to \$500, and used again.

Tracking Options

Finally, satellite telemetry is one of many options for marking raptors. Before deciding to use telemetry we encourage persons to consider carefully (1) their objectives and (2) the possible effects of marking on the birds and their implications for the results. The literature provides many examples of studies in which satellite telemetry has provided valuable information (Table 1). Consultation with manufacturers about options can be very useful, and is especially important for programming the function of transmitters and receivers to maximize performance.

ACKNOWLEDGMENTS

We thank A. Aebischer, P. Howey, B.D. Chancellor, and K. Bates for their helpful comments on drafts of our manuscript.

LITERATURE CITED

- ALERSTAM, T., M. HAKE AND N. KJELLÉN. 2006. Temporal and spatial patterns of repeated migratory journeys by Ospreys. *Anim. Behav.* 71:555–566.
- BATES, K., K. STEENHOF AND M.R. FULLER. 2003. Recommendations for finding PTTs on the ground without VHF telemetry. Proceedings of the Argos Animal Tracking Symposium, 24–26 March 2003, Annapolis, Maryland. Available on a CD from Service Argos, Inc., Largo MD U.S.A.
- BRITTEN, M.W., P. L. KENNEDY, AND S. AMBROSE. 1999. Performance and accuracy evaluation of small satellite transmitters. *J. Wildl. Manage.* 63:1349–1358.
- BRODEUR, S., R. DÉCARIE, D.M. BIRD AND M.R. FULLER. 1996. Complete migration cycle of Golden Eagles breeding in northern Quebec. *Condor* 98:293–299.
- CLS AMERICA. 2003. Proceedings of the Argos Animal Tracking Symposium, 24–26 March 2003, Annapolis, Maryland. CLS America, Largo, MD U.S.A.
- CRAIGHEAD, D. AND R. SMITH. 2003. The implications of PTT location accuracy on a study of Red-tailed Hawks. Proceedings of

- the Argos Animal Tracking Symposium, 24–26 March 2003, Annapolis, Maryland. Available on a CD from Service Argos, Inc., Largo MD U.S.A.
- DOOLEY, J.A., P.B. SHARPE AND D.K. GARCELON. 2004. Abstract: Monitoring movements and foraging of Bald Eagles (*Haliaeetus leucocephalus*) reintroduced on the northern Channel Islands, California using solar Argos/GPS PTTs and VHF telemetry. Pages 26–27 in Program and abstracts: Raptor Research Foundation-California Hawking Club annual meeting, Bakersfield, California, 10–13 November 2004. Raptor Research Foundation, Clovis, CA U.S.A.
- EASTHAM, C.P., J.L. QUINN AND N.C. FOX. 2000. Saker *Falco cherrug* and Peregrine *Falco peregrinus* falcons in Asia; determining migration routes and trapping pressure. Pages 247–258 in R.D. Chancellor and B.-U. Meyburg [EDS.], Raptors at risk. World Working Group on Birds of Prey and Owls, Berlin, Germany and Hancock House, London, United Kingdom.
- ELLIS, D.H., S.L. MOON AND J.W. ROBINSON. 2001. Annual movements of a Steppe Eagle (*Aquila nipalensis*) summering in Mongolia and wintering in Tibet. *Bombay Nat. Hist. Soc.* 98:335–340.
- FULLER, M.R., W.S. SEEGAR AND L.S. SCHUECK. 1998. Routes and travel rates of migrating Peregrine Falcons *Falco peregrinus* and Swainson's Hawks *Buteo swainsoni* in the western hemisphere. *J. Avian Biol.* 29:433–440.
- , D. HOLT AND L.S. SCHUECK. 2003. Snowy Owl movements: variation on the migration theme. Pages 359–366 in P. Berthold, E. Gwinner, and E. Sonnenschein [EDS.], Avian migration. Springer-Verlag, Berlin, Germany.
- , J.J. MILLSPAUGH, K.E. CHURCH AND R.E. KENWARD. 2005. Wildlife radio telemetry. Pages 377–417 in C.E. Braun [ED.], Techniques for wildlife investigations and management, 6th Ed. The Wildlife Society, Bethesda, MD U.S.A.
- GOLDSTEIN, M.I., T.E. LACHER, JR., B. WOODBRIDGE, M.J. BECHARD, S.B. CANAVELLI, M.E. ZACCAGNINI, G.P. COBB, E.J. SCOLLON, R. TRIBOLET AND M.J. COOPER. 1999. Monocrotophos induced mass mortality of Swainson's Hawks in Argentina, 1995–96. *Ecotoxicology* 8:201–214.
- GROS, P. AND J.-P. MALARDÉ. 2006. Argos performance in Europe. *Tracker News* 7:8.
- HAINES, A.M., M.J. MCGRADY, M.S. MARTELL, B.J. DAYTON, M.B. HENKE AND W.S. SEEGAR. 2003. Migration routes and wintering locations of Broad-winged Hawks tracked by satellite telemetry. *Wilson Bull.* 115:166–169.
- HAKE, M., N. KJELLÉN AND T. ALERSTAM. 2001. Satellite tracking of Swedish Ospreys *Pandion haliaetus*: autumn migration routes and orientation. *J. Avian Biol.* 32:47–56.
- , N. KJELLÉN AND T. ALERSTAM. 2003. Age-dependent migration strategy in Honey Buzzards *Pernis apivorus* tracked by satellite. *Oikos* 103:385–396.
- HAYS, G.C., S. AKESSON, B.J. GODLEY, P. LUSCHI AND P. SANTIDRIAN. 2001. The implications of location accuracy for the interpretation of satellite-tracking data. *Anim. Behav.* 61:1035–1040.
- HEDENSTRÖM, A. 1997. Predicted and observed migration speed in Lesser Spotted Eagle *Aquila pomarina*. *Ardea* 85:29–36.
- HENNY, C.J., W.S. SEEGAR, M.A. YATES, T.L. MAECHETLE, S.A. GANUSEVICH AND M.R. FULLER. 2000. Contaminants and wintering areas of Peregrine Falcons, *Falco peregrinus*, from the Kola Peninsula, Russia. Pages 871–878 in R.D. Chancellor and B.-U. Meyburg [EDS.], Raptors at risk. World Working Group on Birds of Prey and Owls, Berlin, Germany and Hancock House, London, United Kingdom.
- HIGUCHI, H., H. SHIU, H. NAKAMURA, A. UEMATSU, K. KUNO, M. SAEKI, M. HOTTA, K. TOKITA, E. MORIYA, E. MORISHITA AND M. TAMURA. 2005. Migration of Honey-buzzards *Pernis apivorus* based on satellite tracking. *Ornithol. Science* 4:109–115.
- HOOVER, M.J., P. MINEAU, M.E. ZACCAGNINI, G.W. WINEGRAD AND B. WOODBRIDGE. 1999. Monocrotophos and the Swainson's Hawk. *Pesticide Outlook* 10: 97–102.
- HOWEY, P. 2002. Useful tips - finding a lost PTT (part 2). Microwave Telemetry, Inc., Newsletter Winter 2000:4. (http://microwave-telemetry.com/newsletters.winter00_page4.pdf) (last accessed 7/6/2006).
- . 2005. Argos performance in Europe. *Tracker News* 6:8.
- KJELLÉN, N., M. HAKE AND T. ALERSTAM. 2001. Timing and speed of migration in male, female and juvenile Ospreys *Pandion haliaetus* between Sweden and Africa as revealed by field observations, radar and satellite tracking. *J. Avian Biol.* 32:57–67.
- LAING, D.K., D.M. BIRD AND T.E. CHUBBS. 2005. First complete migration cycles for juvenile Bald Eagles (*Haliaeetus leucocephalus*) from Labrador. *J. Raptor Res.* 39:11–18.
- LAUNAY, F. AND M.G. MULLER. 2003. Falcon release and migration. *Falco* 22:22–23.
- MARTELL, M.S., C.J. HENNY, P.E. NYE AND M.J. SOLENSKY. 2001. Fall migration routes, timing, and wintering sites of North American Ospreys as determined by satellite telemetry. *Condor* 103:715–724.
- MCGRADY, M.J., T.L. MAECHTLE, J.J. VARGAS, W.S. SEEGAR AND M.C. PORRAS PEÑA. 2002. Migration and ranging of Peregrine Falcons wintering on the Gulf of Mexico coast, Tamaulipas, Mexico. *Condor* 104:39–48.
- , M. UETA, E.R. POTAPOV, I. UTEKHINA, V. MASTEROV, A. LADYGUINE, V. ZYKOV, J. CIBOR, M. FULLER AND W.S. SEEGAR. 2003. Movements by juvenile and immature Steller's Sea Eagles *Haliaeetus pelagicus* tracked by satellite. *Ibis* 145:318–328.
- MEYBURG, B.-U., W. SCHELLER AND C. MEYBURG. 1995a. Migration and wintering of the Lesser Spotted Eagle *Aquila pomarina*: a study by means of satellite telemetry. *J. Ornithol.* 136:401–422.
- , J.M. MENDELSON, D.H. ELLIS, D.G. SMITH, C. MEYBURG AND A.C. KEMP. 1995b. Year-round movements of a Wahlberg's Eagle *Aquila wahlbergi* tracked by satellite. *Ostrich* 66:135–140.
- , C. MEYBURG AND J.-C. BARBRAUD. 1998. Migration strategies of an adult Short-toed Eagle *Circaetus gallicus* tracked by satellite. *Alauda* 66:39–48.
- , J. MATTHES AND C. MEYBURG. 2002. Satellite-tracked Lesser Spotted Eagle avoids crossing water at the Gulf of Suez. *Br. Birds* 95:372–376.
- , P. PAILLAT AND C. MEYBURG. 2003. Migration routes of Steppe Eagles between Asia and Africa: a study by means of satellite telemetry. *Condor* 105:219–227.
- , M. GALLARDO, C. MEYBURG AND E. DIMITROVA. 2004a. Migrations and sojourn in Africa of Egyptian Vultures (*Neophron percnopterus*) tracked by satellite. *J. Ornithol.* 145:273–280.
- , C. MEYBURG, T. BELKA, O. SREIBR AND J. VRANA. 2004b. Migration, wintering and breeding of a Lesser Spotted Eagle (*Aquila pomarina*) from Slovakia tracked by satellite. *J. Ornithol.* 145:1–7.

- , C. MEYBURG, T. MIZERA, G. MACIOROWSKI AND J. KOWALSKI. 2005. Family break up, departure, and autumn migration in Europe of a family of Greater Spotted Eagles (*Aquila clanga*) as reported by satellite telemetry. *J. Raptor Res.* 39:462–466.
- , C. MEYBURG, J. MATTHES AND H. MATTHES. 2006. GPS satellite tracking of Lesser Spotted Eagles (*Aquila pomarina*): home range and territorial behaviour. *Vogelwelt* 127:127–144.
- , C. MEYBURG AND F. FRANCK-NEUMANN. 2007a. Why do female Lesser Spotted Eagles (*Aquila pomarina*) visit strange nests remote from their own? *J. Ornithol.* 148:157–166.
- , C. MEYBURG, J. MATTHES AND H. MATTHES. 2007b. Spring migration, late arrival, temporary mate change and breeding success in the Lesser Spotted Eagle *Aquila pomarina*. *Vogelwelt* 128:21–31.
- MILLSAP, B., T. BREEN, E. MCCONNELL, T. STEFFER, L. PHILLIPS, N. DOUGLASS AND S. TAYLOR. 2004. Comparative fecundity and survival of Bald Eagles fledged from suburban and rural natal areas in Florida. *J. Wildl. Manage.* 68:1018–1031.
- MURRAY, D.L. AND M.R. FULLER. 2000. Effects of marking on the life history patterns of vertebrates. Pages 15–64 in L. Boitani and T. Fuller [Eds.], *Research techniques in ethology and animal ecology*. Columbia University Press, New York, NY U.S.A.
- PESKE, L. AND M.J. MCGRADY. 2005. From the field: a system for locating satellite-received transmitters (PTTs) in the field. *Wildl. Soc. Bull.* 33:307–312.
- RAFANOMEZANTSOA, S., R.T. WATSON AND R. THORSTROM. 2002. Juvenile dispersal of Madagascar Fish-eagles tracked by satellite telemetry. *J. Raptor Res.* 36:309–314.
- ROSE, E.F., W. ENGLISH AND A. HAMILTON. 1993. Abstract: Paired use of satellite and VHF telemetry on rehabilitated Bald Eagles. *J. Raptor Res.* 27:92.
- SCHMUTZ, J.K., C.S. HOUSTON AND G.L. HOLROYD. 1996. Southward migration of Swainson's Hawks: over 10,000 km in 54 days. *Blue Jay* 54:70–76.
- SNYDER, N.F.R., S.R. BEISSINGER AND M.R. FULLER. 1989. Solar radio transmitters on Snail Kites in Florida. *J. Field Ornithol.* 60:171–177.
- SOUTULLO, A., V. URIOS AND M. FERRER. 2006a. How far away in an hour? Daily movements of juvenile Golden Eagles (*Aquila chrysaetos*) tracked with satellite telemetry. *J. Ornithol.* 147:69–72.
- , V. URIOS, M. FERRER AND S.G. PEÑARRUBIA. 2006b. Post-fledging behaviour in Golden Eagles *Aquila chrysaetos*: onset of juvenile dispersal and progressive distancing from the nest. *Ibis* 148:307–312.
- STEENHOF, K., M.R. FULLER, M.N. KOCHERT AND K.K. BATES. 2005. Long-range movements and breeding dispersal of Prairie Falcons from southwest Idaho. *Condor* 107:481–496.
- , K.K. BATES, M.R. FULLER, M.N. KOCHERT, J.O. MCKINLEY AND P.M. LUKACS. 2006. Effects of radio marking on Prairie Falcons: attachment failures provide insights about survival. *Wildl. Soc. Bull.* 34:116–126.
- STRIKWERDA, T.E., M.R. FULLER, W.S. SEEGAR, P.W. HOWEY AND H.D. BLACK. 1986. Bird born satellite transmitter and location program. *Johns Hopkins APL Tech. Digest* 7:203–208.
- THORUP, K., T. ALERSTAM, M. HAKE AND N. KJELLÉN. 2003a. Can vector summation describe the orientation system of juvenile Ospreys and Honey Buzzards? An analysis of ring recoveries and satellite tracking. *Oikos* 103:350–359.
- , T. ALERSTAM, M. HAKE AND N. KJELLÉN. 2003b. Bird orientation: compensation for wind drift in migrating raptors is age dependent. *Proc. Royal Soc. London, B* 270:S8–S11.
- , T. ALERSTAM, M. HAKE AND N. KJELLÉN. 2006a. Traveling or stopping of migrating birds in relation to wind: an illustration for the Osprey. *Behav. Ecol* 17:497–502.
- , M. FULLER, T. ALERSTAM, M. HAKE, N. KJELLÉN AND R. STRANDBERG. 2006b. Do migratory flight paths of raptors follow constant geographical or geomagnetic courses? *Anim. Behav.* 72:875–880.
- UETA, M. AND H. HIGUCHI. 2002. Difference in migration pattern between adult and immature birds using satellites. *Auk* 119:832–835.
- , F. SATO, J. NAKAGAWA AND N. MITA. 2000. Migration routes and differences of migration schedule between adult and young Steller's Sea Eagles *Haliaeetus pelagicus*. *Ibis* 142:35–39.
- WOODBIDGE, B., K.K. FINLEY AND S.T. SEAGER. 1995. An investigation of the Swainson's Hawk in Argentina. *J. Raptor Res.* 29:202–204.

Toxicology

18

CHARLES J. HENNY

USGS Forest and Rangeland Ecosystem Science Center
3200 SW Jefferson Way, Corvallis, OR 97331 U.S.A.

JOHN E. ELLIOTT

Environment Canada, Pacific Wildlife Research Centre
5421 Robertson Road, RR1, Delta, BC, V4K 3N2 Canada

INTRODUCTION

In earlier years (1947–1985), many contaminant-related problems concerning raptors were related to chlorinated hydrocarbon (CH) insecticides, such as DDT, dieldrin, heptachlor, and chlordane, most of which now have been banned in the U.S. and elsewhere. Other contaminants mentioned in the first edition of this manual (Peakall 1987) included mercury, lead, polychlorinated biphenyls (PCBs), and acid deposition, the latter impacting fish populations in poorly buffered lakes and, therefore, adversely affecting Ospreys (*Pandion haliaetus*) and Bald Eagles (*Haliaeetus leucocephalus*). Secondary poisoning of raptors by anticoagulant rodenticides and organophosphorus (OP) pesticides was beginning to be evaluated. The extirpation of the Peregrine Falcon (*Falco peregrinus*) from the eastern U.S. by 1964, and major reductions in numbers elsewhere around the world, was due primarily to DDT, and, perhaps, other CHs. The recovery of the peregrine in the U.S., following the 1972 ban on the widespread use of DDT and much effort in reintroducing the species, and its eventual delisting in 1999 from being an Endangered

Species, was recently told in *Return of the Peregrine* (Cade and Burnham 2003).

Overall, the relative importance of specific contaminant issues today is not the same as discussed in the first edition of this manual, and new issues have emerged. That said persistent CHs still adversely influence some species at selected locations (e.g., DDE-reduced nesting success and significantly thinned the eggshells of some Ospreys breeding along the lower Columbia River in 1997–98, even though the population was increasing at the time [Henny et al. 2004]).

This chapter is subdivided into different classes of environmental contaminants that may adversely affect raptor populations. For each class of contaminants, we present: (1) structure and chemistry (what they are), (2) sources and use patterns (where and how they are used), (3) fate and transport (how mobile they are in the environment), (4) toxicology (what their basic mode[s] of action are), (5) effects criteria (what residue concentration and biochemical response in which tissues should be investigated; Table 1), and (6) techniques for studying field exposure and effects (Table 2).

As a note of caution, residue concentrations in the literature may be presented in several ways, which can be confusing (e.g., wet weight [ww], dry weight [dw], lipid weight [lw]). Sometimes the methods section of a paper must be read carefully to determine which value was used; it is critical to understand this terminology because reported concentrations vary tremendously depending upon how data are presented, as well as with the percent moisture and percent lipid in the tissue examined. Concentrations (C) readily can be converted (e.g., $C_{\text{dry}} = C_{\text{wet}} 100/100 - \% \text{ moisture}$).

Table 1. Selection of estimated toxicity threshold values for contaminants in raptor species^a.

Species	Chemical ^b	Tissue	Effect ^c	Value w.w. (units)	Ref. ^d
Bald Eagle (<i>Haliaeetus leucocephalus</i>)	DDE	Egg	15% reduction in shell thickness	16 mg/kg	1
		Egg	Corresponds to 0.7 young/occupied territory	5.9 mg/kg	2
	Egg	Significant reduction in productivity	12 mg/kg	3	
		Embryo lethality	5.5 mg/kg	2	
	Plasma	Corresponds to 5.9 mg/kg in eggs	41 µg/kg	2	
	Brain	Lowest value poisoned adult	212 mg/kg	4	
	Dieldrin	Brain	Lowest value poisoned adult	3.6 mg/kg	5
	ΣPCBs	Egg	Reduced probability of producing young	20 mg/kg	2
		Plasma	Corresponds to 20 mg/kg in eggs	189 µg/kg	2
	TCDD TEQs	Egg	NOAEL hatching	303 ng/kg	2
		Egg	NOAEL CYP1A induction	135 ng/kg	2
		Egg	LOAEL CYP1A induction	400 ng/kg	2
White-tailed Eagle (<i>H. albicilla</i>)	DDE	Egg	LOAEL productivity	6.0 mg/kg	6
		Egg	Strong reduction in desiccation index	8.5 mg/kg	6
		Egg	Corresponds to 0.7 young/occupied territory	10.5 mg/kg	6
	ΣPCBs	Egg	LOAEL for productivity	25 mg/kg	6
	TCDD TEQs	Egg	LOAEL for embryo mortality	320 ng/kg	6
Osprey (<i>Pandion haliaetus</i>)	DDE	Egg	Corresponds to 0.8 young/occupied nest	4.2 mg/kg	7
	TCDD TEQs	Egg	NOAEL for productivity	162 ng/kg	8
		Egg	NOAEL for hatching	136 ng/kg	9
		Egg	NOAEL for CYP1A induction	36 ng/kg	9
		Egg	LOAEL for CYP1A induction	130 ng/kg	9
American Kestrel (<i>Falco sparverius</i>)	PCB 126	Egg	Embryonic LD ₅₀	65 µg/kg	10
		Egg	Significant increase in malformations and edema	2.3 µg/kg	10
	PCB 77	Egg	Embryonic LD ₅₀	688 µg/kg	10
	ΣPCBs	Egg	Effects on reproductive and endocrine endpoints	34 mg/kg	11,12
	HE	Egg	Reduced productivity	1.5 mg/kg	13
Peregrine Falcon (<i>F. peregrinus</i>)	DDE	Egg	Reduced productivity	15–20 mg/kg	14
	ΣPCBs	Egg	Reduced productivity	40 mg/kg	14
Common Kestrel (<i>F. tinnunculus</i>)	MeHg	Brain	Mortality	25–33 mg/kg	15
	MeHg	Liver	Mortality	50–120 mg/kg	15
Red-tailed Hawk (<i>Buteo jamaicensis</i>)	MeHg	Liver	Mortality	20 mg/kg	16

^a Sensitivity to most contaminants is species-specific. Much additional information on non-raptorial species is available (see Beyer et al. [1996]).

^b DDE = p,p'-dichlorodiphenyl-dichloroethylene; ΣPCBs = sum polychlorinated biphenyl congeners; TCDD TEQs = 2,3,7,8-tetrachlorodibenzo-p-dioxin toxic equivalents; PCB 126 = 3,3',4,4',5-penta-CB (one of the most toxic PCB congeners); PCB 77 = 3,3',4,4'-tetra-CB (one of the most toxic PCB congeners); HE = heptachlor epoxide; MeHg = methylmercury.

^c NOAEL = no-observed-adverse-effect-level; LOAEL = lowest-observed-adverse-effect-level; LD₅₀ = acute oral median lethal dosage.

^d References: 1, Wiemeyer et al. 1993; 2, Elliott and Harris 2002; 3, Nisbet and Risebrough 1994; 4, Garcelon and Thomas 1997; 5, Prouty et al. 1977; 6, Helander et al. 2002; 7, Wiemeyer et al. 1988; 8, Woodford et al. 1998; 9, Elliott et al. 2001; 10, Hoffman et al. 1998; 11, Fernie et al. 2001; 12, Smits et al. 2002; 13, Henny et al. 1983; 14, Peakall et al. 1990; 15, Koeman et al. 1971; 16, Fimreite and Karstad 1971.

Table 2. Examples of studies using recommended techniques in raptor field ecotoxicology.

Chemical(s) of concern	Sampling matrix	Technique(s)	Reference ^a
Persistent organic pollutants	Egg	Salvage unhatched eggs or fragments for chemistry (combined with productivity and other measurements)	1,2,3
	Egg	Sample egg technique (collection of eggs for chemistry) (combined with productivity and other measurements)	4,5,6
	Egg	Laboratory incubation of fresh eggs (chemical analysis of the yolk sacs or of a sibling egg; morphology, histology, biochemistry of organs)	7,8
	Egg	Egg swap experiments (can be combined with collection of eggs and behavioral observations; always combined with productivity, and potentially, other measurements)	9,10
	Major organs: liver, kidney, brain	Mortality monitoring: collection of dead and moribund birds for necropsy and chemistry, biochemistry, and histology	3,11
	Blood	Capture: migrant or breeding birds, residues	12,13
Mercury	Egg	Sample egg technique (see above)	14
	Blood	Nestlings: residues	14
	Feathers	Adults and nestlings: residues	14
	Liver, kidney, brain	Nestlings: residues	14
Lead	Blood	Nestlings, adults: residues, ALAD, protoporphyrin, hemoglobin	15,16
Anti-cholinesterase insecticides	Brain	Cholinesterase activity: dead or moribund birds	17,18
	Blood	Cholinesterase activity: dead or moribund birds	19
	Blood	Cholinesterase activity: captured birds	20
	Crop contents	Chemical residues: dead birds or surgically removed from live,9 poisoned birds	18,21

Note: ALAD = delta-aminolevulinic acid dehydratase.

^aReferences: 1, Ratcliffe 1970; 2, Newton and Galbraith 1991; 3, Newton 1988; 4, Blus 1984; 5, Henny et al. 1983; 6, Henny et al. 2004; 7, Elliott et al. 1996a; 8, Elliott et al. 2001; 9, Wiemeyer et al. 1975; 10, Woodford et al. 1998; 11, Prouty et al. 1977; 12, Henny et al. 1996; 13, Court et al. 1990; 14, DesGranges et al. 1998; 15, Henny et al. 1991; 16, Henny et al. 1994; 17, Henny et al. 1987; 18, Elliott et al. 1996b; 19, Elliott et al. 1997b; 20, Hooper et al. 1989; 21, Henny et al. 1985.

CHLORINATED HYDROCARBON (CH) INSECTICIDES

Chemistry and Toxicology

Matsumura (1985) characterized these synthetic organic insecticides by (1) the presence of carbon, chlorine, hydrogen and sometimes oxygen atoms, including C-Cl bonds, (2) the presence of cyclic carbon chains (including benzene rings), (3) whether or not they were preferentially lipid-soluble, and (4) their stability in the environment. These compounds generally persist in the environment and biomagnify in food chains (some more than others), with raptors at the top of food chains and, especially bird-eating and fish-eating species, being particularly vulnerable. Generally, there are three kinds of CH insecticides: (1) DDT and its analogs (including methoxychlor and dicofol [kelthane]), (2) benzene hexachloride (BHC) isomers including lindane, and (3) cyclodiene compounds (including chlordane, heptachlor, aldrin, dieldrin (HEOD), endrin, toxaphene, mirex, kepone, endosulfan and telodrin. All are neuroactive agents whose modes of action include effects on ion permeability (DDT group) or effects as agents for nerve receptors (BHC and cyclodienes).

These compounds were first introduced in the late 1940s and early 1950s, and, with few exceptions, were banned in most industrialized countries during the 1970s or shortly thereafter. Their principal uses were in agriculture and for disease-vector control. Effects of persistent CH insecticides on raptor populations were widely documented and were catastrophic for some species. Continuing concern reflects their persistence, biomagnification and continued public health use for mosquito control in some countries. In theory, raptors may become exposed to CHs at great distances from application sites due to: (1) atmospheric transport (e.g., elevated concentrations in the Canadian arctic [Barrie et al. 1992]), (2) migratory prey species transporting material from distant sources, or (3) migratory raptors themselves transporting material from distant sources (Henny et al. 1982).

Criteria and Techniques

DDT (and its breakdown product DDE), heptachlor, dieldrin, and perhaps other CH insecticides can cause reduced productivity (Lockie et al. 1969, Ratcliffe 1970, Henny et al. 1983). Unhatched (failed) eggs have been and continue to be analyzed to determine the con-

taminants causing reduced reproductive success (e.g., Wegner et al. 2005). A nonviable Peregrine Falcon egg analyzed in 1960 represents the earliest study of pollutant-related effects on raptors (Moore and Ratcliffe 1962). As Peakall (1987) pointed out, examining eggs is advantageous because it directly examines the target (i.e., the nonviable egg). CH residue concentrations in the egg are directly related to levels in the adult female (Norstrom et al. 1985), which is not necessarily true for other classes of pollutants. CH concentrations reported from nonviable eggs remaining in the nest, after the expected hatch date (a non-random sample), are usually biased towards higher values, if CHs adversely influenced hatchability. Scientists prefer residues from a randomly collected single "sample egg" (Blus 1984) (1 to 2 weeks into incubation) from a series of nests to evaluate possible effects of CHs on success of eggs remaining in the clutch and to document contaminant levels in populations. Collecting a sample egg can cause nest abandonment for some raptor species, such as Bald Eagles (Grier 1969), which negatively influences productivity, whereas for other species, including Ospreys, nests are rarely abandoned after a short visit for egg collection. The reduction for each Osprey egg collected (usually from a three-egg clutch), for example, was only 0.28 young fledged per active nest (Henny et al. 2004; Fig. 1). The sensitivity of eggs to this group of insecticides is species-specific, and as such, no single diagnostic egg concentration can be used for all species, e.g., DDE adversely influences Osprey reproductive success above 4.2 mg/kg (ww) (Wiemeyer et al. 1988), Bald Eagle above 5.9 mg/kg (ww) (Elliott and Harris 2002), and Peregrine Falcon above 15–20 mg/kg (ww) (Peakall et al. 1990). As expected, the degree of eggshell thinning caused by a given egg concentration of DDE, the only CH insecticide known to thin eggshells except for the structurally similar dicofol (Bennett et al. 1990), also varies among families of raptors and even among species within the same family (Peakall 1975). Usually, shell thickness is compared to pre-DDT era norms based upon eggshells in museums.

CH insecticides, especially the cyclodienes, also kill birds, and when dead raptors are found and these insecticides suspected, the brain should be analyzed and residues compared to diagnostic concentrations based on laboratory studies (see criteria in Beyer et al. 1996). Peakall (1996) reviewed the causes of death of Bald Eagles found dead in the U.S. by a network of federal, state, and private investigators from 1966 to 1983. The

Figure 1. Increasing Osprey (*Pandion haliaetus*) populations have pioneered back into some potentially contaminated industrial sites, e.g., Seattle Harbor, U.S.A., where they are again being used as an indicator species to evaluate numerous contaminants. Note Osprey nest with two eggs in the foreground (Photo by J. Kaiser, USGS).



percentage of deaths attributed to dieldrin decreased following a ban on its use (i.e., 13% in 1966–70, 6.5% in 1971–74, 3.0% in 1975–77, and 1.7% in 1978–83). Decreases in mortality and increases in natality in the late 1970s and 1980s were followed by population increases in those species adversely affected in earlier years. The best evidence of the impact of dieldrin poisoning is the long-term study of Eurasian Sparrowhawks (*Accipiter nisus*) in Britain (Newton et al. 1986). A recent re-analysis of these data shows that at least 29% of the sparrowhawks in the area of high cyclodiene use died directly from dieldrin poisoning, which led to a population decline (Sibley et al. 2000). Comparison of temporal trends in populations of Sharpshinned Hawks (*A. striatus*) with both egg residues and usage patterns of dieldrin and DDT in North America support the possibility that dieldrin poisoning also may have impacted North American accipiters (Elliott and Martin 1994). Chlordane, persisting from earlier efforts to control turf pests in parks and gardens, recently poisoned songbirds and raptors, particularly Cooper's Hawks (*A. cooperii*) (Stansley and Roscoe 1999).

Blood plasma can be used to monitor long-term CH residue trends in raptor populations and to evaluate local exposure (Henny and Meeker 1981, Court et al. 1990, Elliott and Shutt 1993, Jarman et al. 1994). Migratory species (both raptors and their prey) often are exposed elsewhere during their travels. Based upon DDE measured in blood plasma of migratory Peregrine Falcons captured on the Texas coast as they departed and returned to the U.S. during migration, Henny et al. (1982) concluded DDE at that time was largely accu-

mulated during winter in Latin America. This study continued for long-term monitoring purposes and, with the use of satellite telemetry to locate breeding and wintering localities, documented the decrease of DDE in arctic-breeding peregrines from the late 1970s to 1994 (Henny et al. 1996).

Two general types of CH studies continue: (1) long-term monitoring of the productivity and population sizes of species previously in trouble, often with egg or blood-plasma collections for residue analyses, and (2) evaluations of potentially sensitive species based upon diet (i.e., fish or bird-eaters) or at locations with limited information.

POLYCHLORINATED BIPHENYLS (PCBS), POLYCHLORINATED DIBENZO-P-DIOXINS (PCDDs), AND POLYCHLORINATED DIBENZOFURANS (PCDFs)

Chemistry and Toxicology

These related chemicals are released to the environment mainly from industrial and commercial chemical sources. Being relatively persistent and volatile, they have dispersed throughout the global environment where they biomagnify, particularly in aquatic food chains. Some of the highest PCB concentrations in biota have been reported in eagle and falcon species, and thus have been investigated as potential factors in populations of raptors with chronic low productivity. Exposure and effects on wildlife, including raptors, have been

reviewed by Hoffman et al. (1996) and Rice et al. (2003).

PCBs were used for a variety of purposes including manufacture of electrical transformers, and formulation of lubricating and cutting oils, pesticides, plastics, paints, etc. More than a billion kilograms were produced worldwide, with a third having been released into the environment (Tanabe 1988). PCB use has been banned or heavily restricted in most countries since the late 1970s.

Neither PCDDs nor PCDFs are deliberately produced commercially, but they are formed either as by-products during synthesis of other chemicals, such as chlorophenolic herbicides, or during combustion of chlorine-containing materials. Incineration of municipal and industrial wastes is the major global source of dioxins, which can be transported long distances and deposited in soils and sediments (Czuczwa et al. 1984).

The number and position of chlorine atoms determines the chemical and biological attributes of each dioxin, furan, or PCB isomer (Fig. 2). More chlorine atoms generally lead to greater fat solubility and resistance to degradation. The most toxic isomers have chlorines at the 2,3,7,8 (PCDD/Ds) or 3, 3',4,4' (PCBs) positions. Those congeners are more planar in shape and readily bind a cellular protein known as the *Ah* or arylhydrocarbon receptor, which leads to a variety of biological responses.

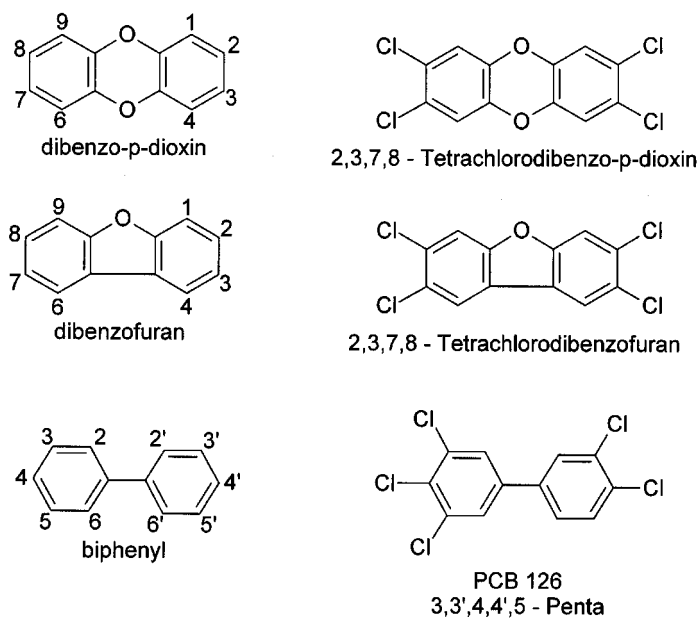


Figure 2. Structure of PCDDs, PCDFs and PCBs.

Toxicity relative to 2,3,7,8-TCDD can be compared using TCDD Toxic Equivalents (TEQs) (Van den Berg et al. 1998). Embryos and growing nestlings are at most risk to TCDD toxicity (Peterson et al. 1993). In laboratory studies, birds of prey including kestrels were less sensitive to PCBs than were quail and chickens (Elliott et al. 1990, 1991, 1997a), but more sensitive than Common Terns (*Sterna hirundo*) (Hoffman et al. 1998). Feeding an environmentally relevant concentration of PCBs to American Kestrels (*F. sparverius*) caused reproductive effects, as well as altered immune and endocrine endpoints (Fernie et al. 2001, Smits et al. 2002). Less persistent congeners, which were less likely encountered in the field, appeared more toxic than the persistent ones.

Toxic effects have been well studied in wild Great Lakes colonial waterbirds. A set of toxic symptoms referred to as GLEMEDS (Great Lakes embryo mortality, edema, and deformities syndrome) has been attributed to exposure to dioxin-like chemicals in gull, tern and cormorant populations (Gilbertson et al. 1991). Bowerman et al. (1994) reported bill deformities in Bald Eagles, but no quantitative relationship between incidence and contaminant exposure. However, kestrel embryos exhibited malformations and edema when eggs were injected with concentrations of PCB-126 at considerably lower levels than measured in Great Lakes Bald Eagles, supporting the contention for dioxin-like chemicals as the cause of observed defects in Bald Eagle chicks (Hoffman et al. 1998).

Despite high concentrations in eggs, it has proved difficult to link PCB concentrations with significant reproductive effects in raptor populations, including peregrines, Ospreys, and accipiters (Newton et al. 1986, Wiemeyer et al. 1988, Peakall et al. 1990, Elliott et al. 2001). Statistical associations between productivity and concentrations of PCBs in eggs were found for Bald Eagles. However, the strong intercorrelation with DDE, which showed a greater effect on productivity (Wiemeyer et al. 1984, 1993), was a confounding factor in that and other studies. A more recent analysis of available data for Bald Eagles showed significant associations between productivity and DDE, but not PCBs (Elliott and Harris 2002). In a long-term study of White-tailed Eagles (*H. albicilla*) in Sweden, Helander et al. (2002) found a correlation for PCBs and the incidence of embryo mortality, but not with productivity. Data from Helander et al. (2002), supported by laboratory evidence (Hoffman et al. 1998, Fernie et al. 2001), indicate that PCBs have affected *Haliaeetus* populations in



Figure 3. Osprey (*Pandion haliaetus*) nest on an easily accessible (with U.S. Coast Guard approval) channel marker near a paper mill on lower Columbia River (River Mile 44) downstream of Portland, Oregon. Ospreys nest at regular intervals along some major river systems and bays which can result in strategic or random sampling of eggs or blood for contaminant evaluation (Photo by J. Kaiser, USGS).

areas of high exposure; however, effects are difficult to separate not only from DDE, but also from ecological factors such as food supply (Dykstra et al. 1998, Elliott and Norstrom 1998, Elliott et al. 1998, Gill and Elliott 2003, Elliott et al. 2005a).

Sublethal effects of dioxin-like chemicals have been reported in some raptors. In a study of Ospreys breeding on a river in Wisconsin, nestlings grew more slowly at a site contaminated with 2,3,7,8-TCDD from a pulp mill than at uncontaminated sites (Woodford et al. 1998; Fig. 3). Induction of cytochrome P450 liver enzymes (CYP1A) of a type responsive to exposure to 2,3,7,8-TCDD toxic equivalents has been reported in embryos of both Ospreys and Bald Eagles breeding near bleached kraft pulp mills (Elliott et al. 1996a, 2001).

Criteria and Techniques

Collection and analysis of eggs is still the preferred method for investigating exposure of raptors to PCBs and related chemicals. The pros and cons of collecting fresh versus unviable eggs, and the use of the sample egg technique discussed in the section on chlorinated hydrocarbon pesticides apply equally here. Concentrations of PCBs in eggs and related compounds diagnostic of effects, such as embryo survival or overall nest success, have not been defined clearly for most species.

Threshold levels for PCBs in eggs were estimated using older analytical methods, such as 40 mg/kg (ww) for peregrines (Peakall et al. 1990). Based on a review and re-analysis of existing data for Bald Eagles, Elliott and Harris (2002) suggested that the reproductive effect threshold was at least 20 mg/kg (ww) total PCBs for Bald Eagles. Helander et al. (2002) determined the lowest observable effect level of 25 mg/kg (ww) (500 mg/kg [lw]) for PCB effects on productivity of White-tailed Eagles. Combining an egg swap design (for more details see Peakall [1987:325] and the discussion below) with regular measurements of chick growth rates, Woodford et al. (1998) suggested a no-observable-adverse-effect-level (NOAEL) of at least 136 ng/kg (ww) for 2,3,7,8-TCDD for the hatchability of Osprey eggs.

Effects of dioxin-like chemicals in birds also can be studied using the technique of laboratory incubation of wild eggs. This approach separates egg-intrinsic effects from adult behavior (egg-extrinsic) and also permits measurement of biomarkers in hatchlings. Using this approach, Elliott et al. (2001) determined a no-effect level for TEQs in Osprey nestlings and a lowest-observable-adverse-effect level of 130 ng/kg (ww) TEQs for hepatic CYP1A induction. Effects of dioxin-like chemicals were studied in laboratory-incubated Bald Eagle eggs (Elliott et al. 1996a) and critical values subsequently recalculated using updated toxic equivalence factors (Elliott and Harris 2002). The results indicate a NOAEL of 135 ng/kg (ww) and lowest-observed-effect-level (LOAEL) of 400 ng/kg for CYP1A induction, and, for embryo toxicity, a NOAEL of 303 ng/kg.

The possible role of dioxin-like chemicals in instances of chronic low reproductive success can be investigated by experimental manipulation of eggs in the field. The logistics of such experiments are complex, given factors such as potential nest abandonment, and the lack of synchronicity in timing of breeding. Embryonic mortality can be caused not only by toxicants within the egg (an intrinsic factor), but also by inadequate parental care caused by the pollutant load (an extrinsic factor), or by a combination of both. These factors can be separated by an egg-exchange experiment between clean and contaminated sites. Adult:Egg combinations in such an experiment (and expected results) include: clean, clean (normal reproduction); clean, contaminated (intrinsic only); contaminated, clean (extrinsic only); and contaminated, contaminated (both intrinsic and extrinsic). For this type of research to be successful, clean and contaminated sites must be

near identical from an ecological perspective, including food availability. Swapping of eggs between treatment and reference sites has provided valuable information in contaminant studies of Ospreys (Wiemeyer et al. 1975), particularly when combined with intensive observation of nesting behavior (Woodford et al. 1998). Nest surveillance, whether directly by an observer or by use of video recording technology, has proved useful in factoring contaminant and ecological variables (Dykstra et al. 1998, Elliott et al. 1998, Gill and Elliott 2003).

Measurement of contaminant levels in blood samples of nestling raptors provides a non-destructive approach, particularly for threatened populations (Elliott and Norstrom 1998, Olsson et al. 2000, Bowerman et al. 2003). Adults also can be trapped either at the nest (Court et al. 1990, Newson et al. 2000), or during migration (Elliott and Shutt 1993), and their blood sampled to assess exposure to PCBs. Diagnostic values for plasma generally are not available, but a value of 189 $\mu\text{g}/\text{kg}$ (ww) total PCBs in nestling plasma was suggested as being correlated with 20 mg/kg (ww) in eggs of Bald Eagles (Elliott and Harris 2002).

LEAD

Chemistry and Toxicology

Sources of lead include lead mining, smelting and refining activities, battery-recycling plants, areas of high vehicular traffic, urban and industrial areas, sewage and spoil-disposal areas, dredging sites, and areas with heavy hunting pressure (Eisler 2000). Most of these sources are local, but until recently, lead exposure from spent shotgun pellets and vehicular traffic were much more widespread. Amounts of lead in roadside soils increased as a direct result of the combustion of gasoline containing organo-lead additives. After about a two-decade phase-out, lead additives in gasoline were totally banned in 1996 for on-road vehicles in the U.S. Since 1998, similar regulations were approved in the European Union, progressively restricting and finally banning the use of leaded gasoline in vehicles.

Lead concentrations in livers of Common Kestrels (*F. tinnunculus*) from both rural and city regions of southeastern Spain decreased significantly between 1995–97 and 2001 (Garcia-Fernandez et al. 2005). The U.S. banned the use of lead shot to hunt waterbirds in 1991. Lead shot was similarly banned in the 1990s in Canada, Denmark, Finland, The Netherlands, and Nor-

way, and in portions of Australia and Sweden (see country policies in Miller et al. [2002]). Thus, two widespread sources of lead were eliminated or were in the process of being reduced in many countries, although lead from the earlier use remains in the environment, and lead shot and bullet use continue for other types of hunting in most countries.

Lead modifies the function and structure of kidney, bone, the central nervous system, and the hematopoietic system, and produces adverse biochemical, histopathological, neuropsychological, fetotoxic, teratogenic, and reproductive effects (Eisler 2000). Lead poisoning in raptors has been fairly well documented since the 1970s. Secondary poisoning from consumption of lead-poisoned or shot waterfowl is believed to be the predominant source of lead exposure for wintering Bald Eagles and Golden Eagles (*Aquila chrysaetos*) (Feierabend and Myers 1984). Upland-foraging raptors and scavengers that typically include game birds and mammals in their diet are also at risk for lead poisoning (Kim et al. 1999, Clark and Scheuhammer 2003, Fry 2003, Wayland et al. 2003).

Criteria and Techniques

Depending on its severity, lead poisoning causes specific clinical signs including depression, foul-smelling breath, lime green feces, nonregenerative anemia, vomiting, diarrhea, ataxia, blindness, and epileptiform seizures (Gilsleider and Oehme 1982). Subclinical or chronic lead exposure usually decreases the ability to hunt and predisposes raptors to injury from environmental hazards such as vehicles, power lines, etc., which could partially explain why many raptors were admitted to rehabilitation centers with miscellaneous trauma (Kramer and Redig 1997). Blood-lead concentrations between 0.2–0.6 mg/kg (ww) were classified as subclinical lead exposure and birds with concentrations between 0.61–1.2 mg/kg classified as clinical (treatable) lead poisoning. Blood-lead concentrations >1.2 mg/kg were invariably associated with death (Kramer and Redig 1997). Blood parameters (g-aminolevulinic acid dehydrase [ALAD], hematocrit, proporphyrin, hemoglobin) have been used in field studies. ALAD inhibition of 80% is often associated with decreased hemoglobin and hematocrits (see references in Henny 2003). Lead-poisoning categories in livers based upon Pain (1996) include: <2 mg/kg (ww) (background), 2–5.9 mg/kg (subclinical), 6–15 mg/kg (clinical) and >15 mg/kg (severe clinical).

Lead poisoning has been documented in at least 14 species of raptors that eat or scavenge prey containing lead shot or bullets (including hunter-wounded birds and mammals). These include California Condor (*Gymnogyps californianus*), Andean Condor (*Vultur gryphus*), King Vulture (*Sarcoramphus papa*), European Honey Buzzard (*Pernis apivorus*), Bald Eagle, White-tailed Eagle, Steller's Sea Eagle (*H. pelagicus*), Western Marsh Harrier (*Circus aeruginosus*), Red-tailed Hawk (*Buteo jamaicensis*), Roughleg (*B. lagopus*), Golden Eagle, Prairie Falcon (*F. mexicanus*), Peregrine Falcon and Great Horned Owl (*Bubo virginianus*) (Locke and Friend 1992, Pain et al. 1994, Kim et al. 1999, Eisler 2000, Clark and Scheuhammer 2003). Most available information was reported from U.S., Canada, Europe and Japan. That most raptors regurgitate pellets (i.e., undigested bones, fur, feathers, and often lead shot) definitely reduces their exposure to lead. Shot has been reported in field-collected pellets, and a laboratory study with five Bald Eagles showed that of 196 shot ingested, only 18 were retained at death, with a median retention time of 2 days (Pattee et al. 1981). Based on these and other findings, Henny (1990) concluded that without pellet casting, the Bald Eagle probably would have become extirpated because of lead poisoning in portions of its range a hundred years ago, long before the lead problem was understood. Thus, lead poisoning could have been much more serious for raptors than it has been.

To avoid various threats, particularly lead poisoning, all remaining California Condors were brought into captivity in 1987. Release of captive-propagated condors began in 1992 and, despite extensive efforts to reduce incidental exposure of condors to lead ammunition fragments, they continue to suffer from acute lead poisoning (Meretsky et al. 2000, Fry 2003). California Condors feed mainly on soft tissues, rarely ingesting bones, hair or feathers (Snyder and Snyder 2000), and thus not only reduced the need to cast pellets, but also increased exposure to ingested lead fragments. Lead is a problem not only in the U.S., but also worldwide. During the winter of 1998–1999 in Hokkaido, Japan, 16 Steller's Sea Eagles and 9 White-tailed Eagles died of lead poisoning after consuming sika deer (*Cervus nippon*) remains containing lead-bullet fragments (Kurosawa 2000).

Lead poisoning of raptors from mining sources has been studied at the Coeur d'Alene (CDA) lead mining and smelting complex in northern Idaho, U.S.A. (Henny et al. 1991, 1994; Henny 2003). Waterfowl were most

affected, due to their consumption of sediment (Beyer et al. 2000). Raptors do not ingest sediment, and most raptors do not digest bones of prey species (a major storage area in vertebrates for lead), thus it became clear why Ospreys, hawks and owls in the CDA basin were less contaminated with lead from mining sources than were waterfowl.

MERCURY

Chemistry and Toxicology

Toxicity of mercury to birds was reviewed by Scheuhammer (1987). Toxicity depends on whether mercury is in the organic or inorganic form. Only a small percentage of inorganic mercury is absorbed, but almost all organic mercury is absorbed by the intestine. Biotic and abiotic methylation in nature of inorganic mercury produces methylmercury (MeHg), which fish accumulate from water and their diet; nearly all mercury in fish flesh is MeHg. MeHg can adversely affect developing neural tissue in birds, with fish-eating birds being especially vulnerable.

Historically, mercury was used extensively in gold and silver extraction, in the chlor-alkali industry, in the manufacture of electrical instruments, in pharmaceuticals, in agricultural fungicides, in the pulp and paper industry as a slimicide, and in the production of plastics (Eisler 2000). Other activities that contribute significantly to the global input of environmentally available mercury include the combustion of fossil fuels; mining and reprocessing of copper and lead, runoff from abandoned cinnabar mines; wastes from nuclear reactors, pharmaceutical plants, and military ordinance facilities; incineration of municipal solid wastes and medical wastes; and disposal of batteries and fluorescent lamps (Eisler 2000). Long-range atmospheric transport of mercury has resulted in elevated mercury loadings great distances from source sites, including remote lakes in Canada (Lucotte et al. 1995). Since 1985, mercury has accumulated in flooded soils of the Florida Everglades at a much higher rate than decades earlier. The increase was attributed to increased global and regional deposition, and is similar to increases reported in Sweden and the northern U.S. (Rood et al. 1995). Elevated mercury concentrations have resulted in closing many lakes and rivers to fishing because of human health concerns. In general, the number of mercury-contaminated fish and wildlife habitats has increased progressively. Increased

mercury concentrations in lakes are attributed to increased atmospheric emissions and to acid rain in poorly buffered systems.

Concerns about mercury exposure of raptors were especially high in Europe and North America during the 1960s and 1970s and are again reaching high levels in more recent years. The earlier interest was associated with the agricultural use of alkyl mercury as a fungicide applied as a seed dressing. This killed many seed-eating birds and secondarily poisoned many raptors (Berg et al. 1966, Jenson et al. 1972). Alkyl mercury was introduced around 1940 and was banned as a seed dressing in Sweden in 1966 (Johnels et al. 1979). Most mercury issues have been associated with aquatic systems and species, but the fungicide use resulted in exposure of upland species, including Eurasian Sparrowhawk, Common Buzzard (*B. buteo*), Merlin (*F. columbarius*), and Common Kestrel.

Contemporary interest in mercury includes: (1) atmospheric deposition from coal-fired power plants worldwide, especially the Arctic and the northeastern U.S. and adjacent Canada, which contaminates fish stocks and exposes fish-eating wildlife, (2) the Amazon Basin where mining operations annually discharge 90–120 tons of mercury into local ecosystems (Nriagu et al. 1992) affecting local breeding populations of birds, including raptors, and perhaps neotropical migrants (e.g., fish-eating Ospreys that nest in eastern North America), and (3) in many parts of the world, localized historic mining sites for mercury, or where mercury was used to extract gold or silver.

Criteria and Techniques

Mercury monitoring procedures have included eggs, liver, kidneys, whole blood and feathers (we recommend that personnel at the analytical chemistry laboratory wash feathers with a metal-free alkaline detergent to remove adhering particulate matter). Shunting MeHg into growing feathers is an important sequestering process in birds. And indeed, essentially all mercury in blood, eggs, and feathers is MeHg. Feathers from museum specimens have been used to provide a long-term evaluation of mercury exposure, although care needs to be taken about consistency in the specific feathers analyzed. Livers and kidneys of many raptors found dead were routinely analyzed only for total mercury (THg). THg concentrations reported in birds “dying of mercury poisoning” showed considerable variation, e.g., White-tailed Eagles (all mg/kg ww): Finland, liver 4.6

to 27.1, kidney 48.6 to 123.1; Germany, liver 48.2, 91, kidney 120; Baltic Sea, liver 30, 11, 33 (see Thompson 1996). This variability may be associated with the presence of differing ratios of inorganic mercury and the more toxic MeHg. It has been known for some time that birds (especially seabirds) demethylate MeHg (the form readily absorbed and usually ingested) and sequester it in the liver and kidneys in the less toxic inorganic form. Forms of mercury present in the liver and kidneys have been analyzed in recent years and provide better insight into mercury toxicity and sequestration. Recent studies of waterbirds along the Carson River in Nevada (a highly-contaminated historic mining site) revealed interesting aspects of mercury toxicodynamics in birds and evidence of some histologic effects (Henny et al. 2002). The theoretical “effect criterion” of mercury in eggs is ~ 0.80 mg/kg (ww) (Heinz 1979, Newton and Haas 1988), but see Oehme (2003). Thompson (1996) rightfully implies that no single mercury criterion in eggs applies to all species, which is similar to the species-specific findings reported earlier for CHs.

Perhaps the best approach to monitoring mercury in raptors is to sample whole blood (highly correlated and 1:1 ratio with MeHg in the liver [Henny et al. 2002]), or to sample newly grown feathers of young (all grown about the same time), which are highly correlated with blood concentrations in young at the time of feather growth. Feathers from adults are more complicated and reflect blood concentrations when the feather was grown (which may represent mercury exposure at different locations for a migratory species), or different degrees of depuration (via feathers) depending upon when in the molt cycle the collected feather was grown. Heinz and Hoffman (2003) reported that once a bird begins ingesting elevated levels of mercury in the diet, it only takes a few days before depositing high levels of mercury in its eggs. High levels of mercury also should appear rapidly in both blood and growing feathers.

ORGANOPHOSPHORUS (OP) AND CARBAMATE (CB) INSECTICIDES

Chemistry and Toxicology

When many of the CH insecticides were banned, they were largely replaced by shorter-lived but more toxic cholinesterase (ChE)-inhibiting OP and CB insecticides. The agents comprising this type of insecticide, which have a common mechanism of action, arise from two

different chemical classes, the esters of phosphoric or phosphorothioic acid (OP) and those of carbonic acid (CB) (Ecobichon 1996). These insecticide classes, primarily developed in the 1950s and 1960s, were generally considered non-persistent and non-bioaccumulative, and, therefore, at low risk for raptor secondary poisoning, occurring through eating intoxicated prey. Many OP and CB compounds have high acute toxicity (low amounts kill vertebrates), especially when compared with the CHs, but they do not bioaccumulate or biomagnify up food chains. Their high acute toxicity results in numerous raptor poisonings and deaths. Secondary poisoning of raptors from these acutely toxic chemicals is most likely from exposure to the unabsorbed compound remaining in the gastro-intestinal tract of the prey (Hill and Mendenhall 1980, Hill 1999), which is in contrast to the importance of residual metabolites accumulated in post-absorptive tissues and fat for CHs. Early reports of OP secondary poisoning involving raptors involved Swamp Harriers (*C. approximans*) in New Zealand killed by parathion and fensulfothion (Mills 1973), and about 400 raptors killed in Israel after eating voles and birds poisoned with monocrotophos (azodrin) (Mendelssohn and Paz 1977).

The principal toxicity of OP and CB pesticides is based on disruption of the nervous system by inhibition of ChE activity in the central nervous system and at neuromuscular junctions with death generally attributed to acute respiratory failure (O'Brien 1967). When an OP or CB binds to ChE, a relatively stable bond is formed and prevents the ChE from deactivating the neurotransmitter, acetylcholine. The clinical signs following an acute exposure include lethargy, labored breathing, excessive bronchial secretion (salivation), vomiting, diarrhea, tremors, and convulsions. These toxic indicators are useful when sick animals are found near an area of recent applications, but the signs are not uniquely different from poisoning by other neurotoxins (Hill 2003).

Criteria and Techniques

OP and CB pesticides have resulted in hundreds of incidents of wildlife mortality from disease vector control and agriculture (including forest and range management). When many dead and moribund animals of mixed species are found in an area of known OP or CB treatment, the casual association may be evident but is not conclusive without biochemical and chemical confirmation (Hill 2003). Proper diagnosis depends upon demonstration of brain ChE inhibition consistent with

levels indicative of toxicity or exposure and chemical detection of residues of the causative agent. Hill (2003) pointed out that the last step is sometimes difficult because neither OP nor CB residues tend to accumulate in tissues, but that a strong inferential diagnosis is possible by demonstrating inhibited brain ChE activity and "detection" of the anti-ChE agent in either ingesta or tissues.

Normal brain ChE values are obtained from raptors (same species, because normal values are species-specific) not exposed to OPs or CBs and used as a basis for comparison. Some published normal values for North American raptors (10 species of vultures, hawks, eagles, falcons, and owls) are available (Hill 1988), but before using them for comparative purposes, it is critical that observed values be based upon the same methodology. The concurrent running of "controls" for normal values on the same instrument is preferred. Another alternative is to use a suitable reactivation technique to determine the degree of inhibition. In cases of OP poisoning, ChE activity can be reactivated *in vitro* by the oxime 2-PAM (Fairbrother 1996), and for carbamated ChE (which is less stable) simple *in vitro* heat will serve as a rapid indicator of CB exposure (Hill and Fleming 1982).

A conservative threshold of 50% inhibition in whole brain ChE activity of a bird found dead is generally considered diagnostic of death from anti-ChE poisoning. Even so, 70–95% is commonly reported for birds killed in nature by OP insecticides (Hill 2003). In contrast, when birds are killed by CB pesticides, whole brain ChE activity often is not nearly as inhibited (ChE levels may vary from near normal to only 70% inhibition). Lesser degrees of ChE inhibition may reflect spontaneous postmortem reactivation of the enzyme (Hill 1989), or that death occurred as a result of initial inhibition of the peripheral nervous system and its control of vital functions prior to the brain being completely inhibited. If immediate analysis is not available, store carcasses frozen (preferably at -80°C) prior to ChE analyses, especially if CBs are suspected. Freezing, however, will hinder the ability to detect other causes of death (e.g., deaths from infectious diseases).

Toxic consequences to raptors from OP and CB applications usually last only a few days, but exceptions do occur. Treatment of cattle with the OP, famphur (poured directly on back of cattle with ladle), kills warble larvae in the blood stream. Black-billed Magpies (*Pica pica*) died several months following application of famphur, and hawks and owls also died from second-



Figure 4. Bald Eagle (*Haliaeetus leucocephalus*) feeding on duck carcass in the Fraser River Delta of British Columbia, Canada. A single duck carcass can attract many Bald Eagles and other raptors, and is a prime vector of insecticides to birds of prey in that environment (Photo by S. Lee, CWS).



Figure 5. Juvenile Bald Eagle (*Haliaeetus leucocephalus*) from Fraser River Delta, British Columbia, Canada, with symptoms of anti-cholinesterase poisoning. Note dilated pupils, clenched talons and the inability to stand. The bird died 2 days later of phorate poisoning (Photo by J. Elliott, CWS).

ary exposure (Henny et al. 1985). Unabsorbed famphur persisted on cattle hair (sampled at weekly intervals) under field conditions for at least 3 months, and magpies that ingested cattle hair died. One Red-tailed Hawk that consumed a magpie died from secondary poisoning 10 days after cattle treatment and another was found incapacitated about 13 days after treatment with blood plasma ChE inhibited 82%.

Plasma ChE, which is more variable than brain ChE, can be used to measure exposure by comparing the observed value to a norm for the species. Caution is indicated for diagnostic use of plasma ChE, because this source of non-specific ChE is more labile and prone to dissociation from inhibitor than is brain ChE (Hill and Fleming 1982). However, acute exposure to potentially lethal levels, at least of OPs, resulted in complete inhibition of plasma ChE activity in many Bald Eagles and other raptors (Elliott et al. 1997b, J. E. Elliott, unpubl. data).

Prior to the famphur study in 1982–83, raptors were not routinely evaluated for OP or CB poisoning. When testing was initiated between March 1984 and March 1985, eight Bald Eagles, two Red-tailed Hawks, and one Great Horned Owl were identified as killed by OP pesticides including fenthion and famphur (Henny et al. 1987). In 1989 and 1990, secondary poisoning of Bald Eagles and Red-tailed Hawks was documented in the Fraser River delta in British Columbia, Canada (Elliott et al. 1996b). Crop contents of the dead raptors, which contained mainly duck parts, included the granular insecticides, carbofuran and fensulfothion (Fig. 4). Elliott et al. (1996b) concluded that enough granular insecticide persists in the low pH conditions of the delta to cause waterfowl kills and secondary poisoning of raptors several months after application, which was supported by subsequent research (Wilson et al. 2002). In 1992–94 additional Bald Eagles and a Red-tailed Hawk in the same area died from phorate, another granular OP insecticide (Elliott et al. 1997b; Fig. 5). Dead eagles usually were found at roost sites rather than in agricultural fields. Persistence of granular formulations causing secondary poisoning is likely not confined to the Fraser River delta, as a similar scenario involving carbofuran poisoning of several hundred waterfowl and some raptors was reported from California (Littrell 1988).

Under laboratory conditions, 14 American Kestrels were presented with House Sparrows (*Passer domesticus*) dermally exposed to Rid-A-Bird (11% fenthion active ingredient). All kestrels died within 3 days (Hunt

et al. 1991). In another scenario, Red-tailed Hawks wintering in orchards in central California were dermally exposed to several dormant-season OP sprays (Hooper et al. 1989, Wilson et al. 1991).

Consumption of freshly sprayed insects by raptors can lead to mortality as well. Large numbers of Swainson's Hawks (*B. swainsoni*) from North America died following grasshopper control in Argentina (Woodbridge et al. 1995). During the 1995–96 austral summer, as many as 3,000 individuals were killed in a single incident and at least 18 different incidents were witnessed totaling about 5,000 Swainson's Hawks (Canavelli and Zacagnini 1996). The OP monocrotophos (first associated with raptor deaths in Israel [Mendelssohn and Paz 1977]) was responsible for the Swainson's Hawk deaths. For additional incidents, see the overall compilation of raptor poisonings by OPs and CBs with emphasis on Canada, U.S., and the U.K. (Mineau et al. 1999), and from the U.S. in 1985–94 (Henny et al. 1999). Raptor poisonings have been frequent under current OP and CB use practices (Henny et al. 1999), although only a few products and formulations have been responsible for most of the incidents.

A high proportion of raptor-poisoning cases in the U.K. resulted from deliberate misuse or abuse of OPs and CBs, whereas the proportion of deliberate poisonings was smaller in North America where problems with labeled uses were as frequent as abuse cases (Mineau et al. 1999).

VERTEBRATE-CONTROL CHEMICALS

Chemistry and Toxicology

A variety of chemicals has been used to control mammal, particularly rodent, and bird populations in urban and agricultural situations. The risk of secondary poisoning of raptors can be high, as many raptor species prey on rodents or other targeted small mammals such as ground squirrels, whereas other species are drawn to scavenge carcasses. Secondary poisoning of raptors has been reported for strychnine (Reidinger and Crabtree 1974) and anti-coagulants (Hegdal and Colvin 1988, Newton et al. 1990, Stone et al. 1999). Chemicals such as sodium monofluoroacetate (Compound 1080) are registered in some jurisdictions for control of livestock predators, whereas CH and anticholinesterase insecticides in particular have seen widespread illegal use for predator control in many countries, and have poisoned

many raptors directly or secondarily (Mineau et al. 1999).

Strychnine is a convulsant that works by lowering the stimulation threshold of spinal reflexes. It is toxic to birds at low concentrations, with LD₅₀s ranging from 2.0 to 24.0 mg/kg (ww). The Golden Eagle LD₅₀ is 4.8 to 8.1 mg/kg (Hudson et al. 1984). Strychnine was widely used in North America in grain baits to control small mammals, including prairie dogs that were considered pests in range and forestlands. Aboveground use was banned in 1983 by the EPA based on secondary poisoning concerns for listed species.

Anti-coagulants now dominate rodent control worldwide. They function by interfering with the action of Vitamin K-dependent clotting factors in the liver, killing the animal via fatal hemorrhaging. The first generation of 4-hydroxy coumarin-based anticoagulants is typified by warfarin, widely used since the 1940s, but to which rodents became resistant in many areas. Second-generation products, such as difenacoum, brodifacoum, and bromadiolone, were subsequently developed. These chemicals are used widely around farm buildings, food storage facilities and in urban settings to control commensal rodents. They have greater potency than the first-generation versions, and also are more persistent and toxic to non-target species. Field and forestry use of second-generation anticoagulants has increased and replaced other poisons such as 1080 and zinc phosphide (Eason et al. 2002).

The hazard to wildlife posed by anticoagulants has been known for some time (Mendenhall and Pank 1980, Townsend et al. 1981). Duckett (1984), for example, reported anticoagulants causing a population collapse of Barn Owls (*Tyto alba*) in Malaysia. A field study in Virginia found that attempts to control orchard voles with brodifacoum resulted in the death of at least five radio-tagged Eastern Screech-Owls (*Megascops asio*) (Hegdal and Colvin 1988). Newton et al. (1990) found that 10% of Barn Owls found dead in Britain contained residues of difenacoum or brodifacoum in their livers, and that exposure to those compounds posed a potential threat to populations. Stone et al. (1999) reported 26 raptors that died from hemorrhage with hepatic residues of anticoagulants, principally brodifacoum, but including warfarin, diphacinone and bromadiolone. Secondary ingestion was the presumed source, and Great Horned Owls (13 cases) and Red-tailed Hawks (seven cases) were the most often poisoned species, although a variety of other raptor species were affected.

Brodifacoum, in particular, has been used to

remove rats from island seabird colonies in various locations, and thus posed a risk to raptors and scavengers. Bald Eagles were exposed to brodifacoum, but with no evidence of adverse effects during a successful rat-eradication program on Langara Island, British Columbia (Howald et al. 1999). Swamp Harriers were among the wildlife poisoned by secondary ingestion of brodifacoum during rat-control projects on islands in New Zealand (Eason et al. 2002).

Techniques

Programs to routinely monitor raptor debilitation and mortality following "vertebrate-control operations" can provide valuable information on incidence of exposure and poisoning (Newton et al. 1990, Stone et al. 1999). Considerable variation exists in avian sensitivity to different anticoagulants and among species to each chemical, which makes it difficult to determine diagnostic liver residue concentrations. Brodifacoum appears to pose a particular risk to raptors not only due to its greater toxicity in general, and to some owls in particular (Newton et al. 1990), but also because of its greater persistence and widespread use. Finding of any residues of brodifacoum in livers of raptors is cause for concern and an indication of potentially lethal exposure of local populations. More intensive monitoring methods, including live-capture for blood sampling of residues and clotting times, and telemetry of raptor populations at risk may be indicated in specific circumstances (Colvin and Hegdal 1988, Howald et al. 1999).

ROTENONE AND OTHER PISCICIDES

As many as 30 piscicides have been used extensively in fisheries management in the U.S. and Canada since the 1930s. Today, only four are registered for general or selective fish control or sampling (Finlayson et al. 2000). The general piscicides include antimycin and rotenone (most extensively used in the U.S.). Lampicides include lampricide and bayluscide. Rotenone is a naturally occurring substance derived from the roots of tropical plants in the bean family (Leguminosae). It has been used for centuries to capture fish in areas where these plants are found naturally. Rotenone inhibits a biochemical process at the cellular level, making it impossible for fish to use the oxygen absorbed in the blood and needed for respiration (Obergh 1967).

Fisheries managers in North America began to use

rotenone for fisheries management in the 1930s. By 1949, 34 states and several Canadian provinces used rotenone to manage fish populations. The piscicide was applied first to ponds and lakes, and then to streams in the early 1960s (Schnick 1974). Finlayson et al. (2000) reported that rotenone residues in dead fish are generally very low (< 0.1 mg/kg [ww]) and not readily absorbed through the gut of the animal eating the fish. While secondary toxicity of rotenone by a fish-eating bird or mammal does not appear to be an issue, the loss of food supply following rotenone treatment of a lake has been shown to reduce reproductive success of fish-eating raptors and loons. Bowerman (1991) reported significantly lower Bald Eagle production rates in Michigan at inland breeding areas treated within 3.2 km of nests for rough fish removal during the treatment year and 2 years following compared to the same sites in non-treatment years (0.57 vs. 1.30 young per occupied nest). Production was even more reduced when treatment locations were within one km of nesting sites (0.39 vs. 1.31). At most lakes in Michigan, fish were manually removed and not killed with rotenone. California mitigated an impact to nesting Bald Eagles by transferring eggs from a nest to an approved eagle recovery program (California Department of Fish and Game 1991). Similarly, Oregon provided supplemental salmon for a pair of Bald Eagles nesting at Hyatt Reservoir in 1990 following rotenone treatment in the fall of 1989; the pair produced one young (J. L. Kaiser, pers. comm.). Michigan mitigated impacts on loons by delaying treatments until chicks fledged (Finlayson et al. 2000).

Ospreys were studied in Oregon associated with an operational use of rotenone. Nesting populations at Hyatt Reservoir (the treatment) and Howard Prairie Reservoir (the control) were studied for two years before application (Henny and Kaiser 1995). Production rates (young/occupied nest) in 1988 and 1989 were similar at both Hyatt (1.48 and 1.44) and Howard Prairie (1.50 and 1.50). Rotenone was applied in autumn 1989 (after Osprey departure) and nesting numbers did not change appreciably in 1990 at Hyatt (11 nests) with no fish present (not yet restocked) or at Howard Prairie (29 nests). Productivity in 1990 was higher at the control reservoir (2.07), and lower at the treatment reservoir (1.00) (C. J. Henny and J. L. Kaiser, unpubl. data), and correlated with low prey delivery rates at Hyatt. Several young died shortly before fledging at Hyatt in 1990, and more days were required to fledge at Hyatt in 1990, which implies food shortages and a slower growth rate. As in the Michigan Bald

Eagle study, production rates at Hyatt Reservoir were depressed in the second and third years after fish removal (0.55 and 1.09 young/occupied nest in 1991 and 1992).

Magnitude of the rotenone effect seems to be related to two factors: (1) the distance to alternative sources of fish, and (2) the timing of the restocking program. After treatment and restocking with game fish, foraging must change to a different cohort of fish (e.g., trout or bass) that are likely less abundant, and more difficult to capture. Bullheads, suckers and chubs, the usual target species of rotenone operations, are usually abundant, prefer shallow water and are slow-moving (i.e., fish characteristics preferred by Ospreys).

EMERGING CONTAMINANTS

Polybrominated Diphenyl Ethers (PBDEs)

The group of chemicals termed persistent organic pollutants (POPs), which includes “legacy” contaminants such as CH pesticides and PCBs, have certainly posed the most serious threat to raptors, including global population declines. Many POPs-type chemicals are considered important in a variety of commercial applications with large quantities of some compounds continuing to be produced. Polybrominated diphenyl ethers (PBDEs) are widely used as flame-retardants in plastic and textile products. PBDEs can affect thyroid hormone and neuronal systems in laboratory animals (Danerud et al. 2001, Danerud 2003) and persist, bioaccumulate and biomagnify in predatory fish, mammals and birds in many ecosystems (de Wit 2002). PBDE residues were reported in Swedish raptors (Jansson et al. 1993), and a variety of isomers (including supposedly non-accumulative types) have been reported in eggs of Peregrine Falcons from Sweden (Lindberg et al. 2004). The eggs of Little Owls (*Athene noctua*) in Belgium collected in 1998–2000 contained PBDEs (Jespers et al. 2005). PBDEs also were found in Osprey eggs from Maryland and Virginia in 2000 and 2001 (Rattner et al. 2004), and from Washington and Oregon in 2002–2004 (C. J. Henny, unpubl. data). Osprey eggs collected between 1991 and 1997 along major rivers in British Columbia had PBDE concentrations that increased 10-fold over that time period, raising concerns over possible health effects if increases continued (Elliott et al. 2005b). Hydroxylated PBDE metabolites, including known thyroxine mimics, recently were reported in blood samples



Figure 6. Juvenile Bald Eagles (*Haliaeetus leucocephalus*) at a nest in the Fraser Valley of British Columbia, Canada. Pre-fledging birds weigh about 4 kg and can provide a large quantity of blood for measurement of contaminants and biomarkers without any adverse effects. Sampling should be scheduled when young are about 6 weeks of age (Photo D. Haycock, CWS).

of Bald Eagle nestlings from British Columbia and California (McKinney et al. 2006; Fig. 6).

Kestrels hatched from eggs injected during incubation with a mixture of PBDEs at a concentration of 1500 ng/g (ww) intended to simulate exposure of Great Lakes Herring Gulls (*Larus argentatus*) exhibited some effects on retinol, thyroid, and oxidative stress parameters (Ferne et al. 2005).

Sulfonated Perfluorochemicals

Perfluoroactane sulfonate (PFOS) was the active ingredient in Scotchguard™ stain and water repellents; perfluoroactanoic acid was used in manufacture of Teflon® and related coatings. In 2000, 3M Corporation committed to eliminate all PFOS use in Scotchguard™ by 2002, while the use of related compounds is undergoing EPA review. These compounds are present as complex mixtures of fluorine atoms substituted on carbon-carbon bonds, which have presented a challenge to the analytical chemist. They have been shown to be persistent and

widely transportable in the environment. There is evidence that structurally similar chemicals affect a variety of biological processes including endocrine function. Blood samples of Bald Eagles from various locations in the U.S. had substantial amounts of PFOS, as did livers of White-tailed Eagles from Poland and Germany (Kannan et al. 2001, 2002). PFOS also were found in Osprey eggs from Chesapeake Bay (Rattner et al. 2004). No data are available to determine whether these chemicals are having a significant effect on wild birds.

Diclofenac

In addition to vultures, which do so regularly, many raptor species scavenge dead prey during periods of inclement weather or when normal prey are scarce. Eagles and buteos, in particular, have been lethally exposed to a wide array of contaminants, particularly lead and various pesticides, from scavenging, as documented elsewhere in this report. As obligate scavengers, vultures are at particular risk of exposure to many chemicals. During the 1990s, catastrophic declines in populations of *Gyps* vulture species took place on the Indian subcontinent (Prakesh et al. 2003). A comprehensive investigation of the causes of mortality in the White-rumped Vulture (*Gyps bengalensis*) in Pakistan identified the main factor as renal failure caused by exposure to diclofenac, a non-steroidal anti-inflammatory drug (Oaks et al. 2004). Diclofenac was readily available in the region and widely used to treat hooved livestock. Vultures appear to consume the drug while feeding on treated livestock, the carcasses of which are typically left for scavengers. There is further evidence that diclofenac also is the major cause of vulture decline in India and probably across the range of the impacted species (Green et al. 2004). Efforts to restrict or alter the use of diclofenac and similar drugs are presently underway, but may be too late to save the white-rumped and possibly the other vulture species in the wild (Green et al. 2004). In May 2006, a letter from the Drug Controller General (India) indicated that diclofenac formulations for veterinary use in India were to be phased out within three months.

Toxins of Biological Origin

We found no reports of raptors poisoned from toxins in algal blooms although sea eagles and Ospreys in particular, could be at risk. Threats from plant toxins are not confined to marine ecosystems. Beginning in the early

1990s in the southeastern U.S., Bald Eagles were found dying from a nervous system condition referred to as avian vacuolar myelinopathy (AVM), thought to originate from feeding on similarly afflicted American Coots (*Fulica americana*) (Thomas et al. 1998). Recent findings point to a toxin present in cyanobacteria, which grow on the common invasive water plant hydrilla, as the cause of AVM (Birrenkott et al. 2004, Wiley et al. 2004).

Such toxic hazards may occur naturally. Halogenated dimethyl bipyrrroles, believed to be of natural origin and structurally similar to products of marine chromobacterium, were found to accumulate in tissues of Bald Eagles and seabirds (Tittlemier et al. 1999). A laboratory dosing study with kestrels found evidence of clinical effects, but concluded that those chemicals did not pose an acute reproductive threat to avian populations (Tittlemier et al. 2003). The increasing perturbation and pollution of ecosystems by exotic species, nutrients and contaminants, along with climatic fluctuations, may increase the future likelihood of similar phenomena.

Newly Registered Chemicals

In addition to the thousands of commercial chemicals presently in use, new products are introduced each year. Many jurisdictions require that all pesticides and pharmaceuticals undergo extensive evaluation for toxicity and environmental fate prior to registration for use (www.epa.gov/opptintr/newchemicals/pubs/expbased.htm). Concern about the development and use of compounds with endocrine-disrupting properties has prompted extensive new screening requirements and requirements to test other types of commercial chemicals (Huet 2000, Gross et al. 2003). Despite those stringent testing protocols, the increased volume and chemical diversity of new products combined with increasing human populations and economic activity almost guarantees that new chemicals or new usage patterns will pose future environmental threats.

Raptors, and, in particular, scavenging species, face increasing and unexpected threats to their survival from the introduction of new commercial chemicals, despite pre-market testing requirements. From the unpredicted effects of DDE on development of eggshells to the exposure and sensitivity of vultures to diclofenac, most of the ecological consequences of those chemicals would not have been identified even by the current relatively rigorous testing procedures.

CONCLUSIONS

With more chemicals registered each year, raptors are exposed to a seemingly endless number of contaminants. At about the time adverse effects of one contaminant or a group of contaminants diminish (usually following much research and a ban or limitation on its use), other contaminants emerge as problems, and the cycle continues. The diversity of raptors inhabiting the planet, with their many feeding strategies and characteristics, place some species in perilous situations. Some traits help raptors cope with selected contaminants. They include pellet-casting by owls and many other raptors which eliminates much ingested lead shot, and demethylation (by many species, especially adults) of toxic MeHg to a less toxic form. However, other traits make entire species or individual populations exceedingly vulnerable to certain contaminants (e.g., flocking behavior of Swainson's Hawks on wintering grounds in Argentina). Scavenging species, including vultures, and many eagles and buteos, particularly are vulnerable to secondary poisoning by feeding on carcasses contaminated by lead shot, pesticides, and veterinary pharmaceuticals. Populations of some species have recovered from DDT. These include the Osprey, which tolerates humans and is now beginning to nest again in many polluted areas, and is being promoted as an indicator species to monitor the health of large rivers, bays, and estuaries, a role the species initially played many years ago. There is an ongoing need to monitor raptor populations, and to investigate reports of poor productivity or unusual mortality and to report it to appropriate authorities.

Readers of this chapter are on the frontline. Many times initial reports of contaminant issues come from field workers who are studying other aspects of raptor biology. We could cite many examples, but space does not permit. The bottom line is that raptor biologists need to remain vigilant.

ACKNOWLEDGMENTS

We appreciate the review of an earlier draft of this chapter by Elwood F. Hill and D. Michael Fry.

LITERATURE CITED

BARRIE, L.A., D. GREGOR, B. HARGRAVE, R. LAKE, D. MUIR, R. SHEARER, B. TRACEY AND T. BIDLAMAN. 1992. Arctic contaminants: sources, occurrence and pathways. *Sci. Total Environ.* 122:1-74.

- BENNETT, J.K., S.E. DOMINGUEZ AND W.L. GRIFFIS. 1990. Effects of dicofol on Mallard eggshell quality. *Arch. Environ. Contam. Toxicol.* 19:907-912.
- BERG, W., A. JOHNELS, B. SJÖSTRAND AND T. WESTERMARK. 1966. Mercury content in feathers of Swedish birds from the past 100 years. *Oikos* 17:71-83.
- BEYER, W.N., G.H. HEINZ AND A.W. REDMON-NORWOOD [EDS.]. 1996. Environmental contaminants in wildlife — interpreting tissue concentrations. Lewis Publishers, Boca Raton, FL U.S.A.
- , D.J. AUDET, G.H. HEINZ, D.J. HOFFMAN AND D. DAY. 2000. Relation of waterfowl poisoning to sediment lead concentrations in the Coeur d'Alene River basin. *Ecotoxicology* 9:207-218.
- BIRRENKOTT, H.H., S.B. WILDE, J.J. HAINS, J.R. FISCHER, T.M. MURPHY, C.P. HOPE, P.G. PARNELL AND W.W. BOWERMAN. 2004. Establishing a food-chain link between aquatic plant material and avian vacuolar myelinopathy in Mallards (*Anas platyrhynchos*). *J. Wildl. Dis.* 40:485-492.
- BLUS, L.J. 1984. DDE in birds' eggs: comparison of two methods for estimating critical levels. *Wilson Bull.* 96:268-276.
- BOWERMAN, W.W., IV. 1991. Factors influencing breeding success of Bald Eagles in upper Michigan. MA thesis, Northern Michigan University, Marquette, MI U.S.A.
- , T.J. KUBIAK, J.B. HOLT, D. EVANS, R.G. ECKSTEIN, C.R. SINDELAR, D.A. BEST AND K.D. KOZIE. 1994. Observed abnormalities in mandibles of nesting Bald Eagles (*Haliaeetus leucocephalus*). *Bull. Environ. Contam. Toxicol.* 53:450-457.
- , D.A. BEST, J.P. GIESY, M.C. SHIELDCASTLE, M.W. MEYER, S. POSTUPALSKY AND J.G. SIKARSKIE. 2003. Associations between regional differences in polychlorinated biphenyls and dichlorodiphenyldichloroethylene in blood of nesting Bald Eagles and reproductive productivity. *Environ. Toxicol. Chem.* 22:371-376.
- CADE, T.J. AND W. BURNHAM [EDS.]. 2003. Return of the peregrine: a North American saga of tenacity and teamwork. The Peregrine Fund, Inc., Boise, ID U.S.A.
- CALIFORNIA DEPARTMENT OF FISH AND GAME. 1991. Northern pike eradication project - Draft subsequent environmental impact report. Inland Fisheries Division, Sacramento, CA U.S.A.
- CANAVELLI, S.B. AND M.E. ZACCAGNINI. 1996. Mortandad de aguilucho langostero (*Buteo swainsoni*) en la region pampeana: primera aproximacion al problema. Instituto Nacional de Tecnologia Agropecuaria, Parana, Entre Rios, Argentina.
- CLARK, A.J. AND A.M. SCHEUHAMMER. 2003. Lead poisoning in upland-foraging birds of prey in Canada. *Ecotoxicology* 12:23-30.
- COLVIN, B.A. AND P.L. HEGDAL. 1988. Procedures for assessing secondary poisoning hazards of rodenticides to owls. Pages 64-71 in S.A. Shumake and R.W. Bullard [EDS.], Vertebrate pest control and management materials. American Society of Testing and Materials, Philadelphia, PA U.S.A.
- COURT, G.S., C.C. GATES, D.A. BOAG, J.D. MACNEIL, D.M. BRADLEY, A.C. FESSER, R.J. PATTERSON, G.B. STENHOUSE AND L.W. OLIPHANT. 1990. A toxicological assessment of Peregrine Falcons *Falco peregrinus tundrius* breeding in the Keewatin District of the Northwest Territories, Canada. *Can. Field-Nat.* 104:255-272.
- CZUCZWA, J.M., B.D. McVEETY AND R.A. HITES. 1984. Polychlori-

- nated dibenzo-p-dioxins and dibenzofurans in sediments from Skskiwit Lake, Isle Royal. *Science* 26:226–227.
- DANERUD, P.O. 2003. Toxic effects of brominated flame retardants in man and wildlife. *Environ. Internat.* 29:841–853.
- , G.S. ERIKSEN, T. JOHANNESSON, P.B. LARSEN AND M. VILUKSELA. 2001. Polybrominated diphenyl ethers: occurrence, dietary exposure and toxicology. *Environ. Health Perspect.* 109 Supplement:49–68.
- DESGRANGES, J.-L., J. RODRIQUE, B. TARDIF AND M. LAPERLE. 1998. Mercury accumulation and biomagnification in Ospreys (*Pandion haliaetus*) in the James Bay and Hudson Bay regions of Quebec. *Arch. Environ. Contam. Toxicol.* 35:330–341.
- DE WIT, C.A. 2002. An overview of brominated flame retardants in the environment. *Chemosphere* 46:583–624.
- DUCKETT, J.E. 1984. Barn owls (*Tyto alba*) and the 'second generation' rat baits utilized in oil palm plantations in Peninsula Malaysia. *Planter* 60:3–11.
- DYKSTRA, C.R., M.W. MEYER, D.K. WARNKE, W.H. KARASOV, D.E. ANDERSEN, W.W. BOWERMAN AND J.P. GIESY. 1998. Low reproductive rates of Lake Superior Bald Eagles: low food delivery rates or environmental contaminants? *J. Great Lakes Res.* 24:32–44.
- EASON, C.T., E.C. MURPHY, G.R.G. WRIGHT AND E.B. SPURR. 2002. Assessment of risks of brodifacoum to non-target birds and mammals in New Zealand. *Ecotoxicology* 11:35–48.
- ECOBICHON, D.J. 1996. Toxic effects of pesticides. Pages 643–689 in C.D. Klaassen [ED.], Casarett and Doull's toxicology: the basic science of poisons, 5th Ed. McGraw-Hill, New York, NY U.S.A.
- EISLER, R. 2000. Handbook of chemical risk assessment: health hazards to humans, plants and animals, Vols. 1-3. Lewis Publishers, Boca Raton, FL U.S.A.
- ELLIOTT, J.E. AND M.L. HARRIS. 2002. An ecotoxicological assessment of chlorinated hydrocarbon effects on Bald Eagle populations. *Reviews Toxicol.* 4:1–60.
- AND P.A. MARTIN. 1994. Chlorinated hydrocarbons and shell thinning in eggs of Accipiter hawks in Ontario, 1986–1989. *Environ. Pollut.* 86:189–200.
- AND R.J. NORSTROM. 1998. Chlorinated hydrocarbon contaminants and productivity of Bald Eagle populations on the Pacific coast of Canada. *Environ. Toxicol. Chem.* 17:1142–1153.
- AND L. SHUTT. 1993. Monitoring organochlorines in blood of Sharp-shinned Hawks *Accipiter striatus* migrating through the Great Lakes. *Environ. Toxicol. Chem.* 12:241–250.
- , S.W. KENNEDY, D.B. PEAKALL AND H. WON. 1990. Polychlorinated biphenyl (PCB) effects on hepatic mixed function oxidases and porphyria in birds. I. Japanese Quail. *Comp. Biochem. Physiol.* 96C:205–210.
- , S.W. KENNEDY, D. JEFFREY AND L. SHUTT. 1991. Polychlorinated biphenyl (PCB) effects on hepatic mixed function oxidases and porphyria in birds. II. American Kestrels. *Comp. Biochem. Physiol.* 99C:141–145.
- , R.J. NORSTROM, A. LORENZEN, L.E. HART, H. PHILIBERT, S.W. KENNEDY, J.J. STEGEMAN, G.D. BELLWARD AND K.M. CHENG. 1996a. Biological effects of polychlorinated dibenzo-p-dioxins, dibenzofurans, and biphenyls in Bald Eagle (*Haliaeetus leucocephalus*) chicks. *Environ. Toxicol. Chem.* 15:782–793.
- , K.M. LANGELIER, P. MINEAU AND L.K. WILSON. 1996b. Poisoning of Bald Eagles and Red-tailed Hawks by carbofuran and fensulfothion in the Fraser delta of British Columbia, Canada. *J. Wildl. Dis.* 32:486–491.
- , S.W. KENNEDY AND A. LORENZEN. 1997a. Comparative toxicity of polychlorinated biphenyls to Japanese Quail (*Coturnix c. japonica*) and American Kestrels (*Falco sparverius*). *J. Toxicol. Environ. Health* 51:57–75.
- , L.K. WILSON, K.M. LANGELIER, P. MINEAU AND P.H. SINCLAIR. 1997b. Secondary poisoning of birds of prey by the organophosphorus insecticide, phorate. *Ecotoxicology* 6:219–231.
- , I.E. MOUL AND K.M. CHENG. 1998. Variable reproductive success of Bald Eagles on the British Columbia coast. *J. Wildl. Manage.* 62:518–529.
- , L.K. WILSON, C.J. HENNY, S.F. TRUDEAU, F.A. LEIGHTON, S.W. KENNEDY AND K.M. CHENG. 2001. Assessment of biological effects of chlorinated hydrocarbons in Osprey chicks. *Environ. Toxicol. Chem.* 20:866–879.
- , L.K. WILSON AND B. WAKEFORD. 2005b. Polybrominated diphenyl ether trends in eggs of aquatic and marine birds from British Columbia, Canada, 1979–2002. *Environ. Sci. Technol.* 39:5584–5591.
- ELLIOTT, K.H., C.E. GILL AND J.E. ELLIOT. 2005a. The influence of tide and weather on provisioning rates of chick-rearing Bald Eagles in Vancouver Island, British Columbia. *J. Raptor Res.* 39:1–10.
- FAIRBROTHER, A. 1996. Cholinesterase-inhibiting pesticides. Pages 52–60 in A. Fairbrother, L.N. Locke, and G.L. Hoft [EDS.], Noninfectious diseases of wildlife, 2nd Ed. University of Iowa Press, Ames, IA U.S.A.
- FEIERABEND, J.S. AND O. MYERS. 1984. A national summary of lead poisoning in Bald Eagles and waterfowl. National Wildlife Federation, Washington, DC U.S.A.
- FERNIE, K.J., J.E. SMITS, G.R. BORTOLOTTI AND D.M. BIRD. 2001. Reproduction success of American Kestrels exposed to dietary polychlorinated biphenyls. *Environ. Toxicol. Chem.* 20:776–781.
- , J.L. SHUTT, G. MAYNE, D.J. HOFFMAN, R.J. LETCHER, K.G. DROUILLARD AND I.J. RITCHIE. 2005. Exposure to polybrominated diphenyl ethers (PBDEs): changes in thyroid, vitamin A, glutathione homeostasis, and oxidative stress in American Kestrels (*Falco sparverius*). *Toxicol. Sci.* 88:375–383.
- FIMREITE, N. AND L. KARSTAD. 1971. Effects of dietary methylmercury on Red-tailed Hawks. *J. Wildl. Manage.* 35:293–300.
- FINLAYSON, B.J., R.A. SCHNICK, R.L. CAITTEUX, L. DEMONG, W.D. HORTON, W. MCCLAY, C.W. THOMPSON AND G.J. TICHACEK. 2000. Rotenone use in fisheries management: administrative and technical guidelines manual. American Fisheries Society, Bethesda, MD U.S.A.
- FRY, D.M. 2003. Assessment of lead contamination sources exposing California Condors. Final Report submitted to California Department of Fish and Game, Sacramento, CA U.S.A.
- GARCIA-FERNANDEZ, A.J., D. ROMERO, E. MARTINEZ-LOPEZ, I. NAVAS, M. PULIDO AND P. MARIA-MOJICA. 2005. Environmental lead exposure in the European Kestrel (*Falco tinnunculus*) from southeastern Spain: the influence of leaded gasoline regulations. *Bull. Environ. Contam. Toxicol.* 74:314–319.
- GARCELON, D.K. AND N.J. THOMAS. 1997. DDE poisoning in an adult Bald Eagle. *J. Wildl. Dis.* 33:299–303.
- GILBERTSON, M., T.J. KUBIAK, J. LUDWIG AND G.A. FOX. 1991. Great

- Lakes embryo mortality, edema, and deformities syndrome (GLEMEDS) in colonial fish-eating birds: similarity to chick edema disease. *J. Toxicol. Environ. Health* 33:455–520.
- GILL, C.E. AND J.E. ELLIOTT. 2003. Influence of food supply and chlorinated hydrocarbon contaminants on breeding success of Bald Eagles. *Ecotoxicology* 12:95–111.
- GILSLEIDER, E. AND F.W. OEHME. 1982. Some common toxicoses in raptors. *Vet. Hum. Toxicol.* 24:169–170.
- GREEN, R.E., I. NEWTON, S. SCHULTZ, A.A. CUNNINGHAM, M. GILBERT, D.J. PAIN, AND V. PRAKESH. 2004. Diclofenac poisoning as a cause of vulture population declines across the Indian subcontinent. *J. Appl. Ecol.* 41:793–800.
- GRIER, J.W. 1969. Bald Eagle behavior and productivity responses to climbing to nests. *J. Wildl. Manage.* 33:961–966.
- GROSS, T.S., B.S. ARNOLD, M.S. SEPULVEDA AND K. McDONALD. 2003. Endocrine disrupting chemicals and endocrine active agents. Pages 1033–1098 in D.J. Hoffman, B.A. Rattner, G.A. Burton, Jr. and J. Cairns, Jr. [EDS.], *Handbook of ecotoxicology*, 2nd Ed. Lewis Publishers, Boca Raton, FL U.S.A.
- HEGDAL P.L. AND B.A. COLVIN. 1988. Potential hazard to Eastern Screech-Owls and other raptors of brodifacoum bait used for vole control in orchards. *Environ. Toxicol. Chem.* 7:245–260.
- HEINZ, G.H. 1979. Methylmercury: reproductive and behavioral effects on three generations of Mallard ducks. *J. Wildl. Manage.* 43:394–401.
- AND D.J. HOFFMAN. 2003. Mercury accumulation and loss in Mallard eggs. *Environ. Toxicol. Chem.* 23:222–224.
- HELANDER, B.A., A. OLSSON, A. BIGNERT, L. ASPLUND AND K. LITZEN. 2002. The role of DDE, PCB, coplanar PCB and eggshell parameters for reproduction in the White-tailed Sea Eagle (*Haliaeetus albicilla*) in Sweden. *Ambio* 31:386–403.
- HENNY, C.J. 1990. Mortality. Pages 140–150 in I. Newton [ED.], *Birds of prey: an illustrated encyclopedic survey by international experts*. Golden Press Pty. Ltd., Silverwater, Australia.
- . 2003. Effects of mining lead on birds: a case history at Couer d'Alene Basin, Idaho. Pages 755–766 in D.J. Hoffman, B.A. Rattner, G.A. Burton, Jr. and J. Cairns, Jr. [EDS.], *Handbook of ecotoxicology*, 2nd Ed. Lewis Publishers, Boca Raton, FL U.S.A.
- AND J.L. KAISER. 1995. Effects of rotenone use to kill "trash" fish on Osprey productivity at a reservoir in Oregon. *J. Raptor Res.* 29:58 (Abstract).
- AND D.L. MEEKER. 1981. An evaluation of blood plasma for monitoring DDE in birds of prey. *Environ. Pollut.* 25A:291–304.
- , F.P. WARD, K. E. RIDDLE AND R.M. PROUTY. 1982. Migratory Peregrine Falcons *Falco peregrinus* accumulate pesticides in Latin America during winter. *Can. Field-Nat.* 96:333–338.
- , L.J. BLUS AND C.J. STAFFORD. 1983. Effects of heptachlor on American Kestrels in the Columbia Basin, Oregon. *J. Wildl. Manage.* 47:1080–1087.
- , L.J. BLUS, E.J. KOLBE AND R.E. FITZNER. 1985. Organophosphate insecticide (famphur) topically applied to cattle kills magpies and hawks. *J. Wildl. Manage.* 49:648–658.
- , E.J. KOLBE, E.F. HILL AND L.J. BLUS. 1987. Case histories of Bald Eagles and other raptors killed by organophosphorus insecticides topically applied to livestock. *J. Wildl. Dis.* 23:292–295.
- , L.J. BLUS, D.J. HOFFMAN, R.A. GROVE AND J.S. HATFIELD. 1991. Lead accumulation and Osprey production near a mining site on the Coeur d'Alene River, Idaho. *Arch. Environ. Contam. Toxicol.* 21:415–424.
- , L.J. BLUS, D.J. HOFFMAN AND R.A. GROVE. 1994. Lead in hawks, falcons and owls downstream from a mining site on the Coeur d'Alene River, Idaho. *Environ. Monit. Assess.* 29:267–288.
- , W.S. SEEGAR AND T.L. MAECHTLE. 1996. DDE decreases in plasma of spring migrant Peregrine Falcons, 1978–1994. *J. Wildl. Manage.* 60:342–349.
- , P. MINEAU, J.E. ELLIOTT AND B. WOODBRIDGE. 1999. Raptor poisoning and current insecticide use: what do isolated kill reports mean to populations? *Proc. Internat. Ornithol. Congr.* 22:1020–1032.
- , E.F. HILL, D.J. HOFFMAN, M.G. SPALDING AND R.A. GROVE. 2002. Nineteenth century mercury: hazard to wading birds and cormorants of the Carson River, Nevada. *Ecotoxicology* 11:213–231.
- , R.A. GROVE, J.L. KAISER AND V.R. BENTLEY. 2004. An evaluation of Osprey eggs to determine spatial residue patterns and effects of contaminants along the lower Columbia River, USA. Pages 369–388 in R.D. Chancellor and B.-U. Meyburg [EDS.], *Raptors Worldwide*. World Working Group for Birds of Prey and Owls, Berlin, Germany and MME, Budapest, Hungary.
- HILL, E.F. 1988. Brain cholinesterase activity of apparently normal wild birds. *J. Wildl. Dis.* 24:51–61.
- . 1989. Divergent effects of postmortem ambient temperature on organophosphorus and carbamate-inhibited brain cholinesterase in birds. *Pest. Biochem. Physiol.* 33:264–275.
- . 1999. Wildlife toxicology. Pages 1327–1363 in B. Ballantyne, T.C. Marrs, and T. Syversen [EDS.], *General and applied toxicology*, Vol. 2, 2nd Ed. Macmillan Reference Ltd., London, United Kingdom.
- . 2003. Wildlife toxicology of organophosphorus and carbamate pesticides. Pages 281–312 in D.J. Hoffman, B.A. Rattner, G.A. Burton, Jr. and J. Cairns, Jr. [EDS.], *Handbook of ecotoxicology*, 2nd Ed. Lewis Publishers, Boca Raton, FL U.S.A.
- AND W.J. FLEMING. 1982. Anticholinesterase poisoning of birds: field monitoring and diagnosis of acute poisoning. *Environ. Toxicol. Chem.* 1:27–38.
- AND V.M. MENDENHALL. 1980. Secondary poisoning of Barn Owls with famphur, an organophosphate insecticide. *J. Wildl. Manage.* 44:676–681.
- HOFFMAN, D.J., C.P. RICE AND T.J. KUBIAK. 1996. PCBs and dioxins in birds. Pages 165–207 in W.N. Beyer, G.H. Heinz, and A.W. Redman-Norwood [EDS.], *Environmental contaminants in wildlife: interpreting tissue concentrations*. Lewis Publishers, Boca Raton, FL U.S.A.
- , M. J. MELANCON, P.N. KLEIN, J.D. EISEMANN AND J.W. SPANN. 1998. Comparative developmental toxicity of planar polychlorinated biphenyl congeners in chickens, American Kestrels and Common Terns. *Environ. Toxicol. Chem.* 17:747–757.
- HOOPER, M.J., P.J. DETRICH, C.P. WEISSKOPF AND B.W. WILSON. 1989. Organophosphorus insecticide exposure in hawks inhabiting orchards during winter dormant spraying. *Bull. Environ. Contam. Toxicol.* 42:651–659.
- HOWALD, G.R., P. MINEAU, J.E. ELLIOTT AND K.M. CHENG. 1999. Brodifacoum poisoning of avian scavengers during rat control on a seabird colony. *Ecotoxicology* 8:431–447.
- HUDSON R.H., R.K. TUCKER AND M.A. HAEGLE. 1984. *Handbook of toxicity of pesticides to wildlife*, 2nd Ed. U.S. Fish and Wildlife

- Service, Resour. Publ. 153, Washington, DC U.S.A.
- HUET, M.-C. 2000. OECD activity on endocrine disrupter test guideline development. *Ecotoxicology* 9:77–84.
- HUNT, K.A., D.M. BIRD, P. MINEAU AND L. SHUTT. 1991. Secondary poisoning hazard of fenthion to American Kestrels. *Arch. Environ. Contamin. Toxicol.* 21:84–90.
- JANSSON, B., R. ANDERSSON, L. ASPLUND, K. LITZEN, K. NYLUND, U. SELLSTROM, U.B. UVEMO, C. WAHLBERG, U. WIDEQVST, T. ODSJO AND M. OLSSON. 1993. Chlorinated and brominated persistent organic compounds in biological samples from the environment. *Environ. Toxicol. Chem.* 12:1163–1174.
- JARMAN, W.M., S.A. BURNS, W.G. MATTOX AND W.S. SEEGAR. 1994. Organochlorine compounds in the plasma of Peregrine Falcons and Gyrfalcons nesting in Greenland. *Arctic* 47:334–340.
- JENSON, S., A.G. JOHNELS, M. OLSSON AND T. WESTERMARK. 1972. The avifauna of Sweden as indicators of environmental contamination with mercury and chlorinated hydrocarbons. *Proc. Internat. Ornithol. Congr.* 15:455–465.
- JESPERS, V., A. COVACI, J. MAERVOET, T. DAUWE, S. VOORSPOELS, P. SCHEPENS AND M. EENS. 2005. Brominated flame retardants and organochlorine pollutants in eggs of Little Owls (*Athene noctua*) from Belgium. *Environ. Pollut.* 136:81–88.
- JOHNELS, A.G., G. TYLER AND T. WESTERMARK. 1979. A history of mercury levels in Swedish fauna. *Ambio* 8:160–168.
- KANNAN, K., J.C. FRANSON, W.W. BOWERMAN, K.J. HANSEN, J.D. JONES AND J.P. GIESY. 2001. Perfluorooctane sulfonate in fish-eating water birds including Bald Eagles and albatrosses. *Environ. Sci. Technol.* 35:3065–3070.
- , K., S. CORSOLINI, J. FALANDYSZ, G. OEHME, S. FOCARDI AND J.P. GIESY. 2002. Perfluorooctanesulfonate and related fluorinated hydrocarbons in marine mammals, fishes and birds from coasts of the Baltic and the Mediterranean Seas. *Environ. Sci. Technol.* 36:3210–3216.
- KIM, E.-Y., R. GATO, H. IWATA, Y. MASUDA, S. TANABE AND S. FUJITA. 1999. Preliminary survey of lead poisoning of Steller's Sea Eagle (*Haliaeetus pelagicus*) and White-tailed Sea Eagle (*Haliaeetus albicilla*) in Hokkaido, Japan. *Environ. Toxicol. Chem.* 18:448–451.
- KOEMAN, J.H., J. GARSEEN-HOEKSTRA, E. PELS AND J.J.M. DEGOEIJ. 1971. Poisoning of birds of prey by methylmercury compounds. *Meded. Faculteit, Landbouwwet* 36:43–49.
- KRAMER, J.L. AND P.T. REDIG. 1997. Sixteen years of lead poisoning in eagles, 1980–95: an epizootiologic view. *J. Raptor Res.* 31:327–332.
- KUROSAWA, N. 2000. Lead poisoning in Steller's Sea Eagles and White-tailed Sea Eagles. Pages 107–109 in M. Ueta and M. McGrady [EDS.], First Symposium on Steller's and White-tailed sea eagles in east Asia. Wild Bird Society, Tokyo, Japan.
- LINDBERG P., U. SELLSTROM, L. HAGGBERG AND C.A. DE WIT. 2004. Higher brominated diphenyl ethers and hexabromocyclododecane found in eggs of Peregrine Falcons (*Falco peregrinus*) breeding in Sweden. *Environ. Sci. Technol.* 38:93–96.
- LITRELL, E.E. 1988. Waterfowl mortality in rice fields treated with the carbamate, carbofuran. *Calif. Fish Game* 74:226–231.
- LOCKE, L.N. AND M. FRIEND. 1992. Lead poisoning of avian species other than waterfowl, Pages 19–22 in D.J. Pain [ED.], Lead poisoning in waterfowl. IWRB Special Publ. No. 16, Brussels, Belgium.
- LOCKIE, J.D., D.A. RATCLIFFE AND R. BALBARRY. 1969. Breeding success and organochlorine residues in Golden Eagles in west Scotland. *J. Appl. Ecol.* 6:381–389.
- LUCOTTE, M., A. MUCCI, C. HILLAIRE-MARCEL, P. PICHET AND A. GRONDIN. 1995. Anthropogenic mercury enrichment in remote lakes of northern Quebec (Canada). *Water Air Soil Pollut.* 80:467–476.
- MATSUMURA, F. 1985. Toxicology of insecticides, 2nd Ed. Plenum Press, New York NY U.S.A.
- MCKINNEY, M.A., L.S. CESH, J.E. ELLIOTT, T.D. WILLIAMS, D.K. GARCELON AND R.J. LETCHER. 2006. Novel brominated and chlorinated contaminants and hydroxylated analogues among North American west coast populations of Bald Eagles (*Haliaeetus leucocephalus*). *Environ. Sci. Technol.* 40:6275–6281.
- MENDELSSOHN, H. AND U. PAZ. 1977. Mass mortality of birds of prey caused by Azodrin, an organophosphorus insecticide. *Biol. Conserv.* 11:163–170.
- MENDENHALL, V.M. AND L.F. PANK. 1980. Secondary poisoning of owls by anticoagulant rodenticides. *Wildl. Soc. Bull.* 8:311–315.
- MERETSKY, V.J., N.F.R. SNYDER, S.R. BEISSINGER, D.A. CLENDENEN AND J.W. WILEY. 2000. Demography of the California Condor: implications for reestablishment. *Conserv. Biol.* 14:957–967.
- MILLER, M.J.R., M.E. WAYL AND G.R. BORTOLOTTI. 2002. Lead exposure and poisoning in diurnal raptors: a global perspective. Pages 224–245 in R. Yosef, M.L. Miller and D. Pepler [EDS.], Raptors in the new millennium. International Birding and Research Center, Eilat, Israel.
- MILLS, J.A. 1973. Some observations on the effects of field applications of fensulfthion and parathion on bird and mammal populations. *Proc. New Zealand Ecol. Soc.* 20:65–71.
- MINEAU, P., M.R. FLETCHER, L.C. GLASER, N.J. THOMAS, C. BRASSARD, L.K. WILSON, J.E. ELLIOTT, L.A. LYON, C.J. HENNY, T. BOLLINGER AND S.L. PORTER. 1999. Poisoning of raptors with organophosphorus and carbamate pesticides with emphasis on Canada, U.S. and U.K. *J. Raptor Res.* 33:1–37.
- MOORE, N.W. AND D.A. RATCLIFFE. 1962. Chlorinated hydrocarbon residues in the egg of a Peregrine Falcon *Falco peregrinus* from Perthshire. *Bird Study* 9:242–244.
- NEWSON, S.C., C.D. SANDAU, J.E. ELLIOTT, S.B. BROWN AND R.J. NORSTROM. 2000. PCBs and hydroxylated metabolites in Bald Eagle plasma: comparison of thyroid hormone and retinol levels. Proc. Internat. Conf. of Environ. Chem., Ottawa, ON, 7–11 May 2000.
- NEWTON, I. 1988. Determination of critical pollutant levels in wild populations, with examples from organochlorine insecticides in birds of prey. *Environ. Pollut.* 55:29–40.
- AND E.A. GALBRAITH. 1991. Organochlorines and mercury in eggs of Golden Eagles *Aquila chrysaetos* from Scotland. *Ibis* 133:115–120.
- AND M.B. HAAS. 1988. Pollutants in Merlin eggs and their effects on breeding. *Br. Birds* 81:258–269.
- , J.A. BOGAN, AND P. ROTHERY. 1986. Trends and effects of organochlorine compounds in sparrowhawk eggs. *J. Appl. Ecol.* 23:461–478.
- , I. WYLLIE AND P. FREESTONE. 1990. Rodenticides in British Barn Owls. *Environ. Pollut.* 68:101–117.
- NISBET, I.C.T. AND R.W. RISEBROUGH. 1994. Relationship of DDE to productivity of Bald Eagles *Haliaeetus leucocephalus* in California and Arizona, USA. Pages 771–773 in B.-U. Meyburg and R.D. Chancellor [EDS.], Raptor Conservation Today. Pica Press, Berlin, Germany.
- NORSTROM, R.J., J.P. CLARK, D.A. JEFFREY, H.T. WONAND AND A.P.

- GILMAN. 1985. Dynamics of organochlorine compounds in Herring Gulls *Larus argentatus*: distribution of [¹⁴C] DDE in free-living Herring Gulls. *Environ. Toxicol. Chem.* 5:41–48.
- NRIAGU, J.O., W.C. PFEIFFER, O. MALM, C.M. MAGALHAES DE SOUZA AND G. MIERLE. 1992. Mercury pollution in Brazil. *Nature* 356:389.
- OAKS, J.L., M. GILBERT, M.Z. VIRANI, R.T. WATSON, C.U. METEYER, B.A. RIDEOUT, H.L. SHIVAPRASAD, S. AHMED, M.J.I. CHAUDHRY, M. ARSHAD, S. MAHMOOD, A. ALI AND A.A. KHAN. 2004. Diclofenac residues as the cause of vulture population decline in Pakistan. *Nature* 427:630–633.
- OBERG, K. 1967. On the principal way of attack of rotenone in fish. *Arch. Zool.* 18:217–220.
- O'BRIEN, R.D. 1967. Insecticides action and metabolism. Academic Press, New York, NY U.S.A.
- OEHME, G. 2003. On the toxic level of mercury in the eggs of *Haliaeetus*. Pages 247–256 in B. Helander, M. Marquiss, and W. Bowerman [EDS.], Sea Eagle 2000. Proceedings from an international sea eagle conference, Swedish Society for Nature Conservation, Stockholm, Sweden.
- OLSSON, A., K. CEDER, A. BERGMAN AND B. HELANDER. 2000. Nestling blood of the White-tailed Sea Eagle (*Haliaeetus albicilla*) as an indicator of territorial exposure to organohalogen compounds: an evaluation. *Environ. Sci. Technol.* 34:2733–2740.
- PAIN, D.J. 1996. Lead in waterfowl. Pages 225–264 in W.N. Beyer, G.H. Heinz, and A.W. Redman-Norwood [EDS.], Environmental contaminants in wildlife: interpreting tissue concentrations. Lewis Publishers, Boca Raton, FL U.S.A.
- , J. SEARS AND I. NEWTON. 1994. Lead concentrations in birds of prey from Britain. *Environ. Pollut.* 87:173–180.
- PATTEE, O.H., S.N. WIEMEYER, B.M. MULHERN, L. SILEO AND J.W. CARPENTER. 1981. Experimental lead shot poisoning in Bald Eagles. *J. Wild. Manage.* 45:806–810.
- PEAKALL, D.B. 1975. Physiological effects of chlorinated hydrocarbons on avian species. Pages 343–360 in R. Hague and V. Freed [EDS.], Environmental dynamics of pesticides. Plenum Press, New York NY U.S.A.
- . 1987. Toxicology. Pages 321–329 in B.A. Giron Pendleton, B.A. Millsap, K.W. Cline, and D.M. Bird [EDS.], Raptor management techniques manual. National Wildlife Federation, Washington, DC U.S.A.
- . 1996. Dieldrin and other cyclodiene pesticides in wildlife. Pages 73–97 in W.N. Beyer, G.H. Heinz, and A.W. Redman-Norwood [EDS.], Environmental contaminants in wildlife: interpreting tissue concentrations. Lewis Publishers, Boca Raton, FL U.S.A.
- , D.G. NOBLE, J.E. ELLIOTT, J.D. SOMERS AND G. ERICKSON. 1990. Environmental contaminants in Canadian Peregrine Falcons, *Falco peregrinus*: a toxicological assessment. *Can. Field-Nat.* 104:244–254.
- PETERSON, R.E., H.M. THEOBALD AND G.L. KIMMEL. 1993. Developmental and reproductive toxicity of dioxins and related compounds: cross species comparisons. *Critical Rev. Toxicol.* 23:283–335.
- PRAKESH, V., D.J. PAIN, A.A. CUNNINGHAM, P.F. DONALD, N. PRAKESH, A. VERMA, R. GARGI, S. SIVAKUMAR AND A.R. RAHMANI. 2003. Catastrophic collapse of Indian White-backed Gyps *bengalensis* and Long-billed Gyps *indicus* vulture populations. *Biol. Conserv.* 109:381–390.
- PROUTY, R.M., W.L. REICHEL, L.N. LOCKE, A.A. BELISLE, E. CRO-MARTIE, T.E. KAISER, T.G. LAMONT, B.M. MULHERN AND D.M. SWINEFORD. 1977. Residues of organochlorine pesticides and polychlorinated biphenyls and autopsy data for Bald Eagles, 1973–74. *Pestic. Monit. J.* 11:134–137.
- RATCLIFFE, D.A. 1970. Changes attributable to pesticides in egg breakage frequency and eggshell thickness in some British birds. *J. Appl. Ecol.* 7:67–115.
- RATTNER, B.A., P.C. MCGOWAN, N.H. GOLDEN, J.S. HATFIELD, P.C. TOSCHIK, R.F. LUKEI, JR., R.C. HALE, I. SCHMITZ-ALFONSO AND C.P. RICE. 2004. Contaminant exposure and reproductive success of Ospreys (*Pandion haliaetus*) nesting in Chesapeake Bay regions of concern. *Arch. Environ. Contam. Toxicol.* 47:126–140.
- REIDINGER, R.F. AND D.G. CRABTREE. 1974. Organochlorine residues in Golden Eagles, United States: March 1964–July 1971. *Pest. Monit. J.* 8:37–43.
- RICE, C.P., P. O'KEEFE AND T. KUBIAK. 2003. Sources, pathways and effects of PCBs, dioxins and dibenzofurans. Pages 501–573 in D.J. Hoffman, B.A. Rattner, G.A. Burton, Jr. and J. Cairns, Jr. [EDS.], Handbook of ecotoxicology, 2nd Ed. Lewis Publishers, Boca Raton, FL U.S.A.
- ROOD, B.E., J.F. GOTTGENS, J.J. DELFINO, C.D. EARLE AND T.L. CRISMAN. 1995. Mercury accumulation trends in Florida Everglades and savannas marsh flooded soils. *Water Air Soil Pollut.* 80:981–990.
- SCHNICK, S. 1974. A review of the literature on the use of rotenone in fisheries. U.S. Fish and Wildlife Service, LaCrosse, WI U.S.A.
- SCHUEHAMMER, A.M. 1987. The chronic toxicity of aluminum, cadmium, mercury and lead in birds: a review. *Environ. Pollut.* 46:263–295.
- SIBLEY, R.M., I. NEWTON AND C.H. WALKER. 2000. Effects of dieldrin on population growth rates of sparrowhawks 1963–1986. *J. Appl. Ecol.* 37:540–546.
- SMITS J.E., K.J. FERNIE, G.R. BORTOLOTTI AND T.A. MARCHANT. 2002. Thyroid hormone suppression and cell-mediated immunomodulation in American Kestrels (*Falco sparverius*) exposed to PCBs. *Arch. Environ. Contam. Toxicol.* 43:338–344.
- SNYDER, N. AND H. SNYDER. 2000. The California Condor, a saga of natural history and conservation. Academic Press, London, United Kingdom.
- STANLEY, W. AND D.E. ROSCOE. 1999. Chlordane poisoning of birds in New Jersey, USA. *Environ. Toxicol. Chem.* 18:2095–2099.
- STONE, W.B., J. OKONIEWSKI AND J.R. STEDELIN. 1999. Poisoning of wildlife with anticoagulant rodenticides in New York. *J. Wildl. Dis.* 35:187–193.
- TANABE, S. 1988. PCB problems in the future: foresight from current knowledge. *Environ. Pollut.* 50:5–28.
- THOMAS, N.J., C.U. METEYER AND L. SILEO. 1998. Epizootic vacuolar myelinopathy of the central nervous system of Bald Eagles (*Haliaeetus leucocephalus*) and American Coots (*Fulica americana*). *Vet. Pathol.* 35:479–487.
- THOMPSON, D.R. 1996. Mercury in birds and terrestrial mammals. Pages 341–356 in W.N. Beyer, G. Heinz, and A.W. Redman-Norwood [EDS.], Environmental contaminants in wildlife: interpreting tissue concentrations. Lewis Publishers, Boca Raton, FL U.S.A.
- TITTELMIER, S.A., R.J. NORSTROM, M. SIMON, W.M. JARMAN AND J.E. ELLIOTT. 1999. Identification and distribution of a novel brominated chlorinated heterocyclic compound in seabird eggs.

- Environ. Sci. Technol.* 33:26–33.
- , J.A. DUFFE, A.D. DALLAIRE, D.M. BIRD AND R.J. NORSTROM. 2003. Reproductive and morphological effects of halogenated dimethyl bipyroles on captive American Kestrels (*Falco sparverius*). *Environ. Toxicol. Chem.* 22:1497–1506.
- TOWNSEND, M.G., M.R. FLETCHER, E.M. ODAM AND P.I. STANLEY. 1981. An assessment of the secondary poisoning hazard of warfarin to Tawny Owls. *J. Wildl. Manage.* 45:242–248.
- VAN DEN BERG, M., L. BIRNBAUM, A.T.C. BOSVELD, B. BRUNSTRÖM, P. COOK, M. FEELEY, J.P. GIESY, A. HANBERG, R. HASEGAWA, S.W. KENNEDY, T. KUBIAK, J.C. LARSEN, F.X.R. VAN LEEUWEN, A.K.D. LIEM, C. NOLT, R.E. PETERSON, L. POELLINGER, S. SAFE, D. SCHRENK, D. TILLITT, M. TYSKLIND, M. YOUNES, F. WÆRN AND T. ZACHAREWSKI. 1998. Toxic equivalency factors (TEFs) for PCBs, PCDDs, and PCDFs for humans and wildlife. *Environ. Health Perspect.* 106:775–792.
- WAYLAND, M., L. K. WILSON, J. E. ELLIOTT, M. J. R. MILLER, T. BOLLINGER, M. MCADIE, K. LANGELIER, J. KEATING, AND J. M. W. FROESE. 2003. Mortality, morbidity and lead poisoning of eagles in western Canada, 1986–98. *J. Raptor Res.* 37:8–18.
- WEGNER, P., G. KLEINSTAUBER, F. BRAUM, AND F. SCHILLING. 2005. Long-term investigation of the degree of exposure of German Peregrine Falcons (*Falco peregrinus*) to damaging chemicals in the environment. *J. Ornithol.* 146:34–54.
- WIEMEYER, S.N., P.R. SPITZER, W.C. KRANTZ, T.G. LAMONT AND E. CROMARTIE. 1975. Effects of environmental pollutants on Connecticut and Maryland Ospreys. *J. Wildl. Manage.* 39:124–139.
- , T.G. LAMONT, C.M. BUNCK, C.R. SINDELAR, F.J. GRAMLICH, J.D. FRASER AND M.A. BYRD. 1984. Organochlorine pesticide, polychlorobiphenyl, and mercury residues in Bald Eagle eggs 1969–79 and their relationships to shell thinning and reproduction. *Arch. Environ. Contam. Toxicol.* 13:529–549.
- , C.M. BUNCK AND A.J. KRYNITZKY. 1988. Organochlorine pesticides, polychlorinated biphenyls and mercury in Osprey eggs 1970–1979 and their relationship to shell thinning and productivity. *Arch. Environ. Contam. Toxicol.* 17:767–787.
- , C.M. BUNCK AND C.J. STAFFORD. 1993. Environmental contaminants in Bald Eagle eggs 1980–1984 and further interpretations of relationships to productivity and shell thickness. *Arch. Environ. Contam. Toxicol.* 24:213–227.
- WILEY, F.E., A.H. BIRRENKOTT, S.B. WILDE, T.M. MURPHY, C.P. HOPE, J.J. HAINS AND W.W. BOWERMAN. 2004. Investigating the link between avian vacuolar myelinopathy and a novel species of cyanobacteria. SETAC 2004, 14–18 November, Portland, OR U.S.A. (Abstract).
- WILSON, B.W., M.J. HOOPER, E.E. LITRELL, P.J. DETRICH, M.E. HANSEN, C.P. WEISSKOPF AND J.N. SEIBER. 1991. Orchard dormant sprays and exposure of Red-tailed Hawks to organophosphates. *Bull. Environ. Contam. Toxicol.* 47:717–724.
- WILSON, L.K., J.E. ELLIOTT, R.S. VERNON AND S.Y. SZETO. 2002. Retention of the active ingredients in granular phorate, terbufos, fonofos, and carbofuran in soils of the Lower Fraser Valley and their implications for wildlife poisoning. *Environ. Toxicol. Chem.* 21:260–268.
- WOODBIDGE, B., K.K. FINLEY AND S.T. SEAGER. 1995. An investigation of the Swainson's Hawk in Argentina. *J. Raptor Res.* 29:202–204.
- WOODFORD J.E., W.H. KRASOV, M.E. MEYER AND L. CHAMBERS. 1998. Impact of 2,3,7,8-TCDD exposure on survival, growth, and behaviour of Ospreys breeding in Wisconsin, USA. *Environ. Toxicol. Chem.* 17:1323–1331.